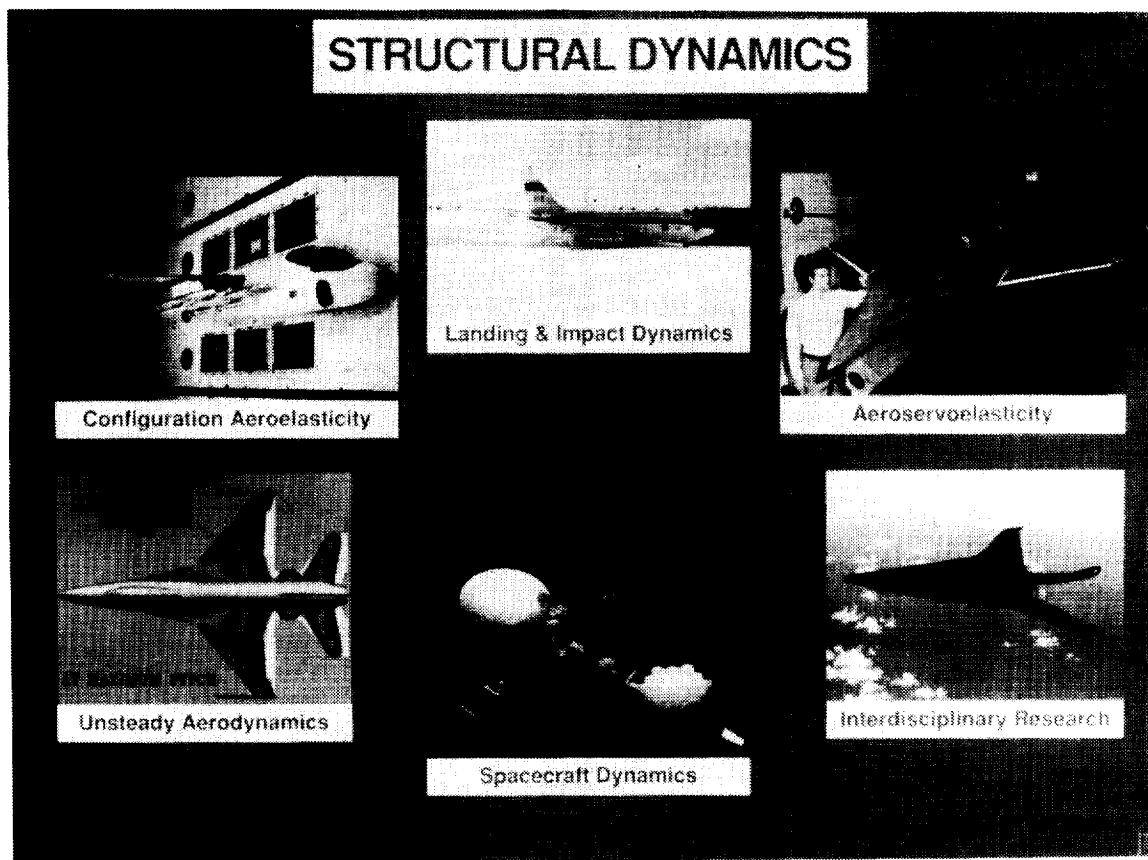


# NASA Technical Memorandum 102770

## STRUCTURAL DYNAMICS DIVISION RESEARCH AND TECHNOLOGY ACCOMPLISHMENTS FOR F.Y. 1990 AND PLANS FOR F.Y. 1991

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**STRUCTURAL DYNAMICS DIVISION**  
**RESEARCH AND TECHNOLOGY ACCOMPLISHMENTS FOR F.Y. 1990**  
**AND PLANS FOR F.Y. 1991**

**SUMMARY**

The purpose of this paper is to present the Structural Dynamics Division's research accomplishments for F.Y. 1990 and research plans for F.Y. 1991. The work under each branch/office (technical area) is described in terms of highlights of accomplishments during the past year and plans for the current year as they relate to 5-year plans and the objectives for each technical area. This information will be useful in program coordination with other government organizations, universities, and industry in areas of mutual interest.

**ORGANIZATION**

The Langley Research Center is organized into directorates as shown in figure 1. Directorates are subdivided into divisions and offices. The Structural Dynamics Division of the Structures Directorate consists of five branches and one office as shown in figure 2. This figure lists the key people in the division which consists of 80 NASA civil servants and 14 members of the Army Aerostructures Directorate, USAARTA, Army Aviation Systems Command collocated at the Langley Research Center. Phone numbers for each organization are given. Recent changes in key positions include the selection of Dr. Woodrow Whitlow as Assistant Head of the Aeroservoelasticity Branch, Mr. Clinton V. Eckstrom as Assistant Head of the Configuration Aeroelasticity Branch, and Mr. Michael G. Gilbert as Assistant Branch Head of the Spacecraft Dynamics Branch. In addition, the Interdisciplinary Research Office was added to the Division. Each branch/office represents a technical area and disciplines under the technical areas are shown in the figure.

The Division conducts analytical and experimental research in six technical areas to meet technology requirements for advanced aerospace vehicles. The research focuses on the long range thrusts shown in figure 3. The Configuration Aeroelasticity Branch (CAB), Unsteady Aerodynamics Branch (UAB), and Aeroservoelasticity Branch (ASEB) all work in the area of the prediction and control of aeroelastic stability and response of aircraft and rotorcraft. The Landing and Impact Dynamics Branch (LIDB) conducts research on the crash dynamics of aircraft structures and on the technology for improving the safety and handling performance of aircraft during ground operations. The Spacecraft Dynamics Branch (SDB) conducts research on the prediction and control of the structural dynamic response of complex space structures. The Interdisciplinary Research Office (IRO) develops methodology for aerospace vehicle design with emphasis on providing analytical methods to quantify interactions among engineering disciplines and to exploit this interaction for improved performance.

## **FUNCTIONAL STATEMENT**

The Division conducts analytical and experimental research in the areas of configuration aeroelasticity, aeroservoelasticity, unsteady aerodynamics, impact and landing dynamics, spacecraft dynamics, and multidisciplinary design to meet technology requirements for advanced atmospheric and space flight vehicles. Develops analytical and computational methods for predicting and controlling aeroelastic instabilities, deformations, vibrations, and dynamic response. Investigates interaction of structure with aerodynamics and control systems, landing dynamics, impact dynamics, and resulting structural response. Evaluates structural configurations embodying new material systems and/or advanced design concepts for general application and for specific classes of new aerospace vehicles. Develops methodology for aircraft and spacecraft design using integrated multidisciplinary methods. Uses a broad spectrum of test facilities to validate analytical and computational methods and advanced configuration and control concepts. Develops research techniques to demonstrate safety from aeroelastic instabilities for new airplanes, helicopters, and space launch vehicles. Test facilities include the Transonic Dynamics Tunnel, the General Rotor Aeroelastic Laboratory, the Impact Dynamics Research Facility, the Aircraft Landing Dynamics Facility, the Space Structures Research Laboratory, and the Structural Dynamics Research Laboratory.

## **FACILITIES**

The Structural Dynamics Division has four major facilities available to support its research as shown in figure 4.

The Transonic Dynamics Tunnel (TDT) is a maximum Mach 1.2 continuous flow, variable pressure wind tunnel with a 16-square-foot test section which normally uses air or a heavy gas (R-12) as the test medium. The maximum Reynolds number obtainable is approximately 10 million per foot in heavy gas and 3 million per foot in air. The TDT is a unique "National" facility that is used almost exclusively for testing of aeroelastic phenomena. Semi-span, sidewall mounted models and full-span sting mounted or cable-mounted models are used for aeroelastic studies of fixed wing aircraft. In addition, the Aeroelastic Rotor Experimental System (ARES) test stand is used in the tunnel to study the aeroelastic characteristics of rotor systems. The General Rotor Aeroelastic Laboratory (GRAL), located in an adjacent building, is used to set up the ARES test stand in preparation for entry into the TDT and for rotorcraft studies in hover. The TDT Data Acquisition System is capable of simultaneous support of tunnel tests, GRAL tests and model checkout in the Calibration Lab. A major facility upgrade to improve the heavy gas reclamation system is now in progress. Operations with subatmospheric capability and air as the test medium will continue until mid February 1991 after which operations will be restricted to atmospheric pressure air until the end of March when all tunnel operations will be shut down for several months. The heavy gas reclamation system upgrade is scheduled for completion in November 1991 after which normal operations with both air and heavy gas will resume.

The Aircraft Landing Dynamics Facility (ALDF) is capable of testing various types of landing gear systems at velocities up to 200 knots on a variety of runway surfaces under many types of simulated weather conditions. The ALDF consists of a 2800-foot long rail



system, a 2.0 million pound thrust propulsion system, a test carriage, and an arrestment system. Test articles can be subjected to vertical loads up to 65,000 pounds or sink rate of 20 feet per second on a wide variety of runway surface conditions. The facility provides for testing at speeds and sizes pertinent to large transport aircraft, fighter aircraft, and the Space Shuttle Orbiter.

The Impact Dynamics Research Facility (IDRF) is capable of crash testing full-scale general aviation aircraft and helicopters under controlled conditions. The facility is a 220-foot high, 400-foot long gantry structure which is the former Lunar Landing Facility. General aviation aircraft and helicopters weighing up to 20,000 pounds can be tested up to 60 mph using a free-swing pendulum approach. Attitudes can be adjusted for desired pitch, roll, and yaw parameters. Impact surfaces can be concrete or dirt. High-speed motion pictures and 90 data channels are available to record the crash event. A vertical test apparatus is attached to one leg of the facility for drop testing structural components. The facility is used to support in-house research and other agency programs (Army, Air Force, FAA).

The Structural Dynamics Research Laboratory (SDRL) is designed for conducting research experiments on the dynamics and control of flexible spacecraft structures. The facilities in this laboratory include the 16 meter Thermal Vacuum Chamber, the Main Backstop Area, and the Tower Test Area. These facilities provide a variety of environmental simulation capabilities, including acceleration, vacuum and thermal radiation. The chamber has a 55-foot diameter, hemispherical dome with a 64-foot high peak, flat floor and option for a large centrifuge or a rotating platform. Access is by an airlock door and an 18 x 20-foot test specimen door. A vacuum level of 10 torr can be achieved within 120 minutes and, with diffusion pumps,  $10^{-4}$  torr vacuum can be achieved within 160 minutes. A temperature variation of 100°F can be obtained in the chamber by using 250-square-feet of portable radiant heaters and liquid nitrogen cooled-plates. The Backstop Area is dominated by the 38-foot high backstop of I-beam construction. Test areas around this fixture are 15 x 35 x 38 feet high and a tower 12 x 12 x 95 feet high, both equipped with hydraulic and pneumatic supply lines. There are various sizes of hoists and accessible platforms for suspension system attachment, instrumentation installation, and test viewing. Closed-circuit television is available for monitoring research studies. Test articles can be excited by several types of actuators and small shakers. State-of-the-art capability is available for signal conditioning and processing including GenRad 2515 digital signal processing systems and a VAX 11-780/EAI 2000 hybrid computer system for simulation and on-line test control.

The Space Structures Research Laboratory (SSRL) is a large open room of dimensions 75 x 84 x 67 feet high. It has a truss framework spanning most of the ceiling area from which lightweight test articles can be supported. A hoist having a capability of approximately 2 tons is available. Access is through a 12 x 12-foot door. A 10 x 10-foot backstop is available in one corner. A control room equipped for structural and structural dynamics data acquisition and analysis equipment is available. Test equipment such as electromagnetic shakers, sensors, and signal conditioning equipment is shared with the SDRL and similar closed-circuit test monitoring and support are available.

## **F.Y. 1990 ACCOMPLISHMENTS**

### **Configuration Aeroelasticity Branch**

The Configuration Aeroelasticity Branch conducts research (fig. 5) to develop the aeroelastic understanding and prediction capabilities to apply new aerodynamic and structural concepts to future flight vehicles and to determine and to solve the aeroelastic problems of current designs as well as to evaluate the aeroelastic characteristics of new rotor systems. Present activities and future plans for the major activity areas are presented in figure 6.

The Configuration Aeroelasticity F.Y. 1990 accomplishments listed below are highlighted in figures 7 through 16.

#### **Aircraft Aeroelasticity:**

- Statically Unstable Model Flown Successfully Using Onboard Stability Augmentation System in TDT
- Aileron Buzz Characteristics are Determined for Several NASP Wing Configurations
- Navy Advanced Fighter Shown Free From Flutter in TDT Tests
- Effects of Thermal Gradients on Structural Vibration Frequencies Investigated
- Flutter Characteristics Defined for Trail Rotor Model in TDT

#### **Benchmark Models:**

- First Benchmark-Model-Program Test Successfully Completed

#### **Rotorcraft Aeroelasticity:**

- TDT Tests Enhance Knowledge of Helicopter Rotor Nodalization Method
- Aeromechanical Stability Data Base for Parametric Hingeless Rotor Expanded

#### **TDT Facility Operations:**

- Modifications to Transonic Dynamics Tunnel Heavy Gas Reclamation System in Progress
- TDT Data Acquisition System Improvements Implemented

### **Unsteady Aerodynamics Branch**

The Unsteady Aerodynamics Branch (UAB) conducts research (fig. 17) to develop, validate, and apply a set of Computational Fluid Dynamics (CFD) methods for predicting steady and unsteady aerodynamic airloads and the aeroelastic characteristics of flight vehicles. The branch also supports research activities aimed at the generation of experimental data bases needed for computer code validation. Current research topics reflect a major emphasis on accurately predicting transonic aeroelastic phenomena, such as wing "flutter-speed dip" and aileron "buzz." Recently, research topics such as dynamic vortex-structure interactions, dynamic loads and buffet prediction have also become important areas of investigation within the UAB. Interest in these latter topics is due to the emerging importance of the high angle-of-attack maneuvering flight capabilities demonstrated by a number of current high performance aircraft. A computational methodology which can be used to accurately and efficiently predict this wide range of

unsteady aerodynamic and aeroelastic phenomena should be based upon a number of different CFD mathematical formulations. The CFD methods developed within the UAB include Transonic Small Disturbance methods, Euler equation methods, and Reynolds-averaged Navier-Stokes based techniques. The branch research program is outlined in figure 18 which shows the 5-year plan for the development of aerodynamic analysis methods and aeroelastic prediction techniques. The plan also provides for UAB participation in the Structural Dynamics Division's Benchmark Models Program (BMP). This experimental effort includes participation in both the TDT wind tunnel tests, as well as pretest and post-test CFD analysis activities.

The Unsteady Aerodynamics F.Y. 1990 accomplishments listed below are highlighted in figures 19 through 30.

**Transonic Small Disturbance CFD Methods:**

- HiSAIR Vehicle Airloads Predicted Using CAP-TSD Code
- The Volterra-Wiener Theory of Nonlinear Systems Applied to the Modeling of Nonlinear Aerodynamic Responses Using CAP-TSD
- Effects of Finite-Difference Mesh and Time Step in Solution of the Transonic Small Disturbance Equation

**Euler/Navier-Stokes CFD Methods:**

- Conical Euler Method Developed to Study Unsteady Vortical Flows About Rolling Delta Wings
- Unsteady Flow Around Delta Wings with Symmetric and Asymmetric Leading-Edge Flaps Oscillations
- CFD Simulates Active Control of Delta Wing Rocking Motion
- Automated Spatial Adaption Procedure Developed For Accurate Unsteady Flow Analysis
- Three-Dimensional Flux-Split Euler Algorithm for Unstructured Grids Validated for Steady Flow

**Computer Graphics Methods:**

- Graphics Code Developed to Permit Visualization of CFD Results For 3-D Unstructured Meshes

**Experimental Investigations:**

- Liquid Crystals Used for Flow Visualization in TDT Benchmark Model Tests
- Transonic Shock-Induced Dynamics of a Flexible Wing with an 18% Circular Arc Airfoil Determined in TDT
- Reynolds Number Effects on Unsteady Pressure Studied in 0.3M Cryo Tunnel

**Aeroservoelasticity Branch**

The Aeroservoelasticity Branch conducts research (fig. 31) to enhance modeling and analysis methods to accurately determine the aeroelastic characteristics of flexible flight vehicles; to formulate advanced algorithms for designing control systems to alleviate undesirable structural and aeroelastic response; to integrate structures, aerodynamics, and controls into a multidisciplinary preliminary design capability; to develop advanced finite

element, structural optimization, aeroelastic tailoring, and aeroelastic stability methods; to perform wind tunnel and flight experiments for obtaining data to validate the new and improved methodologies; and to provide technical support to advanced NASA and DOD projects for insuring that the flight envelope of the vehicle is free of unstable aeroelastic phenomena or adverse structural response. The research is equally applicable to both fixed wing and rotorcraft airframe structures including rotorcraft blade designs. The scope of this work is more explicitly identified in figure 32 which shows the branch's 5-year plan.

The Aeroservoelasticity Branch F.Y. 1990 accomplishments listed below are highlighted by figures 33 through 49.

**Analysis Methodology and Applications:**

- Nonlinear Unsteady Aerodynamics Improve Prediction of Transonic Aeroelastic Behavior of the AFW Model
- Flutter Control Successfully Demonstrated in the TDT Using the Active Flexible Wing Wind-Tunnel Model
- Aeroservoelastocity Successfully Demonstrated on Generic Hypersonic Vehicle
- Optimization Scheme Used to Obtain Maximum Gust Loads for Nonlinear Aircraft
- Digital Control System Stability and Robustness Determined On-Line During Wind-Tunnel Testing
- Hot Bench Simulation Used to Test Functionality of AFW Digital Controller
- Turbulence in the Transonic Dynamics Tunnel (TDT) Measured Using Hot-Wire/Film Anemometry

**Design Methodology:**

- Simultaneous Optimal Design Demonstrated for Aeroservoelastic Systems
- Digital Controller Using Real-Time UNIX Operating System Successfully Damps Structural Response
- Feasibility of Using Adaptive Materials to Alleviate Aeroelastic Instabilities Established
- Digital Feedback Systems for Active Control of Aircraft Wing Loads During Roll Maneuvers
- Active Static Aeroelastic Control Using Adaptive Materials

**Rotorcraft Structural Dynamics:**

- Predicted Dynamic Characteristics Validated for Warping-Prone Extension-Twist-Coupled Composite Tubes
- Preliminary Design Method for Predicting the Effects of Damping Treatment on Structural Vibrations
- Extension-Twist Coupling Concept Demonstrated in TDT
- Government/Industry/Assessment of DAMVIBS Program Completed
- Development of Dynamics Optimization Code for Rotorcraft Airframe Structures

**Landing and Impact Dynamics Branch**

The Landing and Impact Dynamics Branch has two major facilities (fig. 50), the Aircraft Dynamics Facility (ALDF) and the Impact Dynamics Research Facility (IDRF), for conducting research. The landing dynamics group of the branch conducts research to advance technology for safe, economical all-weather aircraft ground operations including the

development of new landing gear systems. The group coordinates in-house research, grants, and contracts with the U.S. tire industry to achieve the technology required. The impact dynamics group conducts research to obtain a better understanding of response characteristics of generic composite aircraft components subjected to crash loading conditions and to develop/enhance analytical tools capable of predicting response of composite structures. In-house research, grants, and contracts are also utilized to achieve the technology and to develop better structural concepts capable of providing energy absorption and reduced crash loads. The work of the Landing and Impact Dynamics Branch is more clearly identified in figure 51 which shows the 5-year plan of the disciplines in both landing and impact dynamics along with their expected results.

The Landing and Impact Dynamics Branch F. Y. 1990 accomplishments listed below are highlighted by figures 52 to 59.

**Impact Dynamics:**

- Commonality in Failure Behavior Identified for Metal and Composite Aircraft Structures Under Crash Loads
- Impact Tests Used to Qualify Honeycomb Energy Absorbing Attenuators for CETA Emergency Brake
- Comparison of Predicted and Experimental Scale Effects in Strength of Composite Beams
- Various Nonlinear Finite Element Analysis Tools Compared Using Experimental Data From Composite Beam Column Study
- Effect of Floor Location on Failure Behavior of Composite Aircraft Fuselage Frame Concept Determined Analytically

**Landing Dynamics:**

- Sensitivity Derivatives Developed to Streamline Future Tire Design Procedures
- Variable Yaw System Reduces Tire Characterization Test Time
- Runway Surface Traction and Radial Tire Program

**Spacecraft Dynamics Branch**

The Spacecraft Dynamics Branch (fig. 60) conducts research and focused technology studies on the dynamics and control of flexible spacecraft. Analysis and prediction methods are developed for application to such spacecraft as Space Station Freedom, Earth-observing science platforms, and Solar System exploration spacecraft. Methods are verified and improved through experiments on research hardware. Advanced test and data analysis methods for improving the accuracy and speed of ground tests to simulate on-orbit behavior and/or to verify spacecraft and spacecraft components for flight are also developed. Significant ongoing emphasis is on interdisciplinary experiments on the control of flexible spacecraft, scale models for spacecraft development, and advanced algorithms for system identification. On-orbit verification methods and experiments are a long-term goal. The scope of this work is more explicitly identified in figure 61 which shows the 5-year plan of the organization's major thrusts and their expected result.

The Spacecraft Dynamics Branch F.Y. 1990 accomplishments listed below are highlighted in figures 62 through 71.

**Controls-Structures Interaction:**

- Control Of Flexible Mini-Mast Demonstrated by CSI Investigators
- Closed-Loop Control of CSI Evolutionary Model Testbed Initiated
- Discrete LQG Controller Design for a 10-Bay Truss Model
- Control System Failure Detection

**Dynamic Test and Verification Methods:**

- DSMT Hybrid-Scale Model Fabricated for Early Configuration Assembly Tests
- Analytical Simulation Confirms Feasibility of Space Station Modal Identification Experiment
- Space Structures Research Laboratory Placed in Operation

**Dynamic Analysis and System Identification:**

- A New Recursive System Identification Method Developed and Successfully Demonstrated Using a 10-Bay Truss Structure
- Method Developed For Expansion of Measured Mode Shapes
- Nonlinear Joint Modeling Study

Interdisciplinary Research Office

The Interdisciplinary Research Office (fig. 72) conducts research aimed at the development, validation, and application of analytical methods for aerospace vehicle design wherein the interactions among all appropriate disciplines are accounted for and exploited. The research program includes the areas of optimization methods, sensitivity analysis, approximate and design-oriented analysis, proper accounting for discipline coupling in analysis and design, strategies for decomposing large complex problems into manageable subproblems, and applications to problems of agency interest. Current application areas include high-speed aircraft, rotorcraft, and controls-structure integrated design of spacecraft. The 5-year plan for the research program shown in figure 73 indicates the current activities and their goals.

The Interdisciplinary Research Office F.Y. 1990 accomplishments listed below are highlighted in figures 74 through 81.

**Optimization:**

- Integrated Rotorcraft Optimization
- Integrated Controls-Structure Optimization for a Large Space Structure
- Model Rotor Blade Successfully Optimized for Hover Performance

**Sensitivity Analysis:**

- Aerodynamic Sensitivity Analysis Capability Developed for Helicopter Rotors in Axial Flight
- Shape Sensitivity Analysis of Static and Dynamic Aeroelastic Responses

**Approximate and Design-Oriented Analysis:**

- Differential-Equation-Based Method Provides Accurate Approximation for Vibration Frequencies and Mode Shapes
- Coupled Multiple-Method Structural Analysis Method Demonstrated

**Decomposition:**

- Application of a Knowledge-Based Tool to Understand HISAIR Data Flow

## **PUBLICATIONS**

The F.Y. 1990 accomplishments of the Structural Dynamics Division resulted in a number of publications. The publications are listed below by organization in the categories of journal publications, formal NASA reports, conference presentations, contractor reports, technical briefs, and patents.

### **Division Office**

#### **NASA Formal Reports:**

1. Doggett, R. V., Jr.; Soistmann, D. L.; Spain, C. V.; Parker, E. C.; and Silva, W. A.: Experimental Transonic Flutter Characteristics of Two 72°-Sweep Delta-Wing Models. NASA TM-101669, November 1989, 19 p.
2. Smith, J. G.; Gardner, J. E.: Structural Dynamics Division Research and Technology Accomplishments for F.Y. 1989 and Plans for F.Y. 1990. NASA TM-101683, January 1990, 193 p.

### **Configuration Aeroelasticity Branch**

#### **Journal Publications:**

3. Brooks, T. F.; Booth, W. R., Jr.; Jolly, J. Ralph, Jr.; Yeager, W. T., Jr.; and Wilbur, M. L.: Reduction of Blade-Vortex Interaction Noise Through Higher Harmonic Pitch Control. Technical Note published in the Journal of the American Helicopter Society, Vol. 35, No. 1, January 1990.
4. Bohlmann, J. D.; Eckstrom, C. V.; and Weisshaar, T. A.: Static Aeroelastic Tailoring for Oblique Wing Lateral Trim. Journal of Aircraft, Vol. 27, No. 6, June 1990.
5. Eckstrom, Clinton V.; Seidel, David A.; and Sandford, Maynard C.: Unsteady Pressure and Structural Response Measurements on an Elastic Supercritical Wing. Journal of Aircraft, Vol. 27, No. 1, January 1990, p. 75-80.

#### **Formal NASA Reports:**

6. Singleton, Jeffrey D.; Yeager, William T.; and Wilbur, Matthew L.: Performance Data From a Wind-Tunnel Test of Two Main-Rotor Blade Designs for a Utility-Class Helicopter. NASA TM-4183, AVSCOM TM 90-B-004, June 1990.
7. Dansberry, Bryan E.; Rivera, José A., Jr.; and Farmer, Moses G.: An Experimental Study of Tip Shape Effects on the Flutter of Aft-Swept, Flat-Plate Wings. NASA TM-4180, June 1990.



#### Conference Presentations:

8. Cole, Stanley R.: Effects of Spoiler Surfaces on the Aeroelastic Behavior of a Low-Aspect-Ratio Rectangular Wing. Presented at the AIAA/ASME/ ASCE/AHS/ASC 31st Structures, Structural Dynamics and Materials Conference, Long Beach, CA, April 1990. AIAA Paper No. 90-0981. Also available as NASA TM-102622.
9. Durham, Michael H.; Cole, Stanley R.; Cazier, F. W., Jr.; Keller, Donald F.; Parker, Ellen C.; and Wilkie, W. Keats: Experimental Transonic Flutter Characteristics of Supersonic Cruise Configurations. Presented at the AIAA/ASME/ASCE/AHS/ASC 31st Structures, Structural Dynamics and Materials Conference, Long Beach, CA, April 1990. AIAA Paper No. 90-0979. Also available as NASA TM-102638.
10. Ricketts, Rodney H.: Experimental Aeroelasticity History, Status, and Future in Brief. Presented at the AIAA/ASME/ASCE/AHS/ASC 31st Structures, Structural Dynamics and Materials Conference, Long Beach, CA, April 1990. AIAA Paper No. 90-0978. Also available as NASA TM-102651.

#### Patents:

11. Farmer, Moses D.: Cable Suspended Windmill. Patent Number 4,894,554, dated January 1990.

### **Unsteady Aerodynamics Branch**

#### Journal Publications:

12. Batina, J. T.: Unsteady Euler Airfoil Solutions Using Unstructured Dynamic Meshes. AIAA Journal, Vol. 27, No. 5, May 1990, p. 1381-1388.
13. Mohr, R. W.; Batina, J. T.; and Yang, H. T. Y.: Mach Number Effects on Transonic Aeroelastic Forces and Flutter Characteristics. Journal of Aircraft, Vol. 26, No. 11, November 1989, p. 1038-1046.
14. Rausch, R. D.; Batina, J. T.; and Yang H. T. Y.: Euler Flutter Analysis of Airfoils Using Unstructured Dynamic Meshes, Journal of Aircraft, Vol. 27, May 1990, p. 436-443.

#### Formal NASA Reports:

15. Edwards, J. W.: Assessment of Computational Prediction of Tail Buffeting. NASA TM-101613, January 1990.
16. Lee, E. M.; and Batina, J. T.: Conical Euler Solution for a Highly-Swept Delta Wing Undergoing Wing-Rock Motion. NASA TM-102609, March 1990.

Conference Presentations:

17. Batina, J. T.: Accuracy of an Unstructured-Grid Upwind-Euler Algorithm for the ONERA M6 Wing. Presented at the Accuracy of Unstructured Grid Techniques Workshop, January 16-17, 1990, Hampton, VA. Proceedings pending.
18. Batina, J. T.: Implicit Flux-Split Euler Schemes for Unsteady Aerodynamic Analysis Involving Unstructured Dynamic Meshes. Presented at the AIAA 31st Structures, Structural Dynamics and Materials Conference, Long Beach, CA, April 2-4, 1990. AIAA Paper No. 90-0936-CP. Also available as NASA TM-102732, November 1990.
19. Batina, J. T.: Three-Dimensional Flux-Split Euler Schemes Involving Unstructured Dynamic Meshes. Presented at the AIAA 21st Fluid Dynamics, Plasmadynamics, and Lasers Conference, Seattle, WA, June 18-20, 1990. AIAA Paper No. 90-1649. Also available as NASA TM-102731, November 1990.
20. Batina, J. T.: Development of Unstructured Grid Methods for Steady and Unsteady Aerodynamic Analysis. Presented at the 17th Congress of the International Council of the Aeronautical Sciences, Stockholm, Sweden, September 9-14, 1990. ICAS Paper No. 90-6.9.4. Also available as NASA TM-102730, November 1990.
21. Bland, S. R.: Personal Computer Study of Finite-Difference Methods for the Transonic Small Disturbance Equation. Presented at the Third International Congress of Fluid Mechanics, Cairo, Egypt, January 2-4, 1990. In Proceedings p. 527-543. Also available as NASA TM-102582.
22. Edwards, John W.: Unsteady Aerodynamics: Physical Issues and Numerical Predictions. Presented at the Third International Congress of Fluid Mechanics, Cairo, Egypt, January 2-4, 1990. In Proceedings, Vol. 1, p. 99-115.
23. Edwards, J. W.: Unsteady Airloads Due to Separated Flow on Airfoils and Wings. Presented at the AGARD 70th Structures and Materials Panel Meeting, Sorrento, Italy, April 2-6, 1990. AGARD CP-483, Paper No. 16, September 1990.
24. Kleb, W. L.; Batina, J. T.; and Williams, M. H.: Temporal-Adaptive Euler/Navier-Stokes Algorithm for Unsteady Aerodynamic Analysis of Airfoils Using Unstructured Dynamic Meshes. Presented at the AIAA 21st Fluid Dynamics, Plasmadynamics, and Lasers Conference, Seattle, WA, June 18-20, 1990. AIAA Paper No. 90-1650.
25. Malone, J. B.; Narramore, J. C.; and Sankar, L. N.: An Airfoil Design Method for Viscous Flows. Presented at the Fifteenth Southeastern Conference of Applied Mechanics, Atlanta, GA, March 22-23, 1990. (Proceedings in Developments in Theoretical and Applied Mechanics, Vol XV, College of Engineering, Georgia Institute of Technology, p.463-470, 1990.)
26. Narramore, J. C.; Malone, J. B.; and Vermeland, R.: Application of a New Navier-Stokes Inverse Method to the Design of Advanced Airfoils. Presented at the 46th

Annual Forum of the American Helicopter Society, Washington, D.C., May 21-23, 1990.

27. Robinson, B. A.; Batina, J. T.; and Yang, H. T. Y.: Aeroelastic Analysis of Wings Using the Euler Equations With a Deforming Mesh. Presented at the AIAA 31st Structures, Structural Dynamics and Materials Conference, Long Beach, CA, April 2-4, 1990. AIAA Paper No. 90-1032.
28. Silva, W. A.; and Bennett, R. M.: Using Transonic Small Disturbance Theory for Predicting the Aeroelastic Stability of a Flexible Wind-Tunnel Model. Presented at the AIAA/ASME/ASCE/AHS/ASC 31st Structures, Structural Dynamics and Materials Conference, Long Beach, CA, April 2-4, 1990, AIAA Paper No. 90-1033. Also available as NASA TM-102617, March 1990, 12 p.
29. Silva, W. A.; and Bennett, R. M.: Predicting the Aeroelastic Behavior of a Wind-Tunnel Model Using Transonic Small Disturbance Theory. Presented at the 17th Congress of the International Council of the Aeronautical Sciences, Stockholm, Sweden, September 9-14, 1990. ICAS Paper No. 90-1.1.1, Vol. 1, p. 1-10, ICAS Proceedings.

#### Contractor Reports:

30. Weinberg, B. C.; Chen, S-Y; Thoren, S. J.; and Shamroth, S. J.: Extension of a Three-Dimensional Viscous Wing Flow Analysis. (NAS1-18140 Scientific Research Associates, Inc.) NASA CR-182023, May 1990, 54 p.
31. Weinberg, B. C.; Chen, S-Y; Thoren, S. J.; and Shamroth, S. J.: Extension of a Three-Dimensional Viscous Wing Flow Analysis - User's Manual - VISTA 3-D Code. (NAS1-18140 Scientific Research Associates, Inc.) NASA CR-182024, May 1990, 105 p.

### **Aeroservoelasticity Branch**

#### Journal Publications:

32. Arbuckle, P.; Buttrill, C.; and Zeiler, T. A.: Simulation Model-Building Procedure for Dynamic Systems Integration. AIAA Journal of Guidance, Control, and Dynamics, November/December 1989, Vol. 12, No. 6, p. 894-900.
33. Gilbert, M. G.: An Analytical Sensitivity Method for Use in Integrated Aeroservoelastic Aircraft Design. Journal of Mechanical Systems and Signal Processing, May 1990, p. 215-231.
34. Lakin, W. D.; and Kvaternik, R. G.: An Integrating Matrix Formulation for Buckling of Rotating Beams Including the Effects of Concentrated Masses. International Journal of Mechanical Sciences, Vol. 31, No. 8, 1989, p. 569-577.

35. Perry, B. III; Pototzky, A. S.; and Woods, J. A.: NASA Investigation of a Claimed "Overlap" Between Two Gust Response Analysis Methods. AIAA Journal of Aircraft, Vol 27, No. 7, September 1990, p. 605-611.
36. Woods, J. A.; Gilbert, M. G.; and Weisshaar, T.: Parametric Aeroelastic Stability Analysis of a Generic X-Wing Aircraft. AIAA Journal of Aircraft, Vol 27, No. 7, July 1990.
37. Young, Maurice I.: On Dynamics Stability Boundaries for Binary Systems. Journal of Sound and Vibration, Vol. 136, No. 3, February 8, 1990.
38. Young, Maurice I.: On Lightly Damped Linear Systems. Journal of Sound and Vibration, Vol. 139, No. 3, June 22, 1990.

Formal NASA Reports:

39. Sleeper, R. K.: Spanwise Measurements of Vertical Components of Atmospheric Turbulence. NASA TP-2963, April 1990.

Conference Presentations:

40. Gilbert, M. G.; Pototzky, A. S.; Heeg, J.; Dunn, H. J.; Spain, C. V.; and Soistmann, D. L.: The Application of Active Controls Technology to a Generic Hypersonic Aircraft Configuration. Presented at the Seventh National Aero-Space Plane Technology Symposium, Cleveland, OH, October 23-27, 1989. NASA TM-101689, December 1989. Also available as NASP TM-1097, May 1990.
41. Heeg, J.; Gilbert, M. G.; and Pototzky, A. S.: Static and Dynamic Aeroelastic Characterization of an Aerodynamically-Heated Generic Hypersonic Aircraft Configuration. Presented at the AIAA/ASME/ASCE/AHS/ASC 31st Structures, Structural Dynamics and Materials Conference, Long Beach, CA, April 2-4, 1990. Also available as NASA CP-3064.
42. Heeg, J.; Gilbert, M. G.; and Pototzky, A. S.: Active Control of Aerothermoelastic Effects for a Conceptual Hypersonic Aircraft. Presented at the AIAA Guidance, Navigation, and Controls Conference, Portland, OR, August 20-22, 1990.
43. Lake, R. C.: Investigation of the Use of Extension-Twist Coupling in Composite Rotor Blades for Application to Tiltrotor Aircraft. Presented at the Third Technical Workshop on Dynamics and Aeroelastic Stability Modeling of Rotorcraft Systems, Durham, NC, March 12-14, 1990. Abstract and viewgraphs published in Proceedings.
44. Mukhopadhyay, V.; Pototzky, A. S.; and Fox, M.: A Scheme for Theoretical and Experimental Evaluation of Multivariable System Stability Robustness. Presented at the Ninth American Control Conference, San Diego, CA, May 23-25, 1990. Paper No. FP-14-15.

45. Noll, T.; Perry, B., III; and Gilbert, M. G.: Aeroservoelasticity, Current Trends and Future Expectations. Presented at the Australian Aeronautical Conference, Melbourne, Australia, October 9-11, 1989. Published in the Proceedings, p. 176-180.
46. Noll T.: Aeroservoelasticity. Presented at the AIAA Structures, Structural Dynamics and Materials Conference, Long Beach, CA, April 3-5, 1990. AIAA Paper No. 90-1073-CP. Also available as NASA TM-102620, March 1990.
47. Perry, B., III; Mukhopadhyay, V.; Hoadley, S. T.; Cole, S. R.; Buttrill, C. S.; and Houck, J. A.: Digital-Flutter-Suppression-System Investigations for the Active Flexible Wing Wind-Tunnel Model. Presented at the AIAA/ASME/ASCE/AHS/ASC 31st Structures, Structural Dynamics and Materials Conference, Long Beach, CA, April 2-4, 1990. AIAA Paper No. 90-1074-CP. Also available as NASA TM-102618, March 1990.
48. Perry, B., III; Mukhopadhyay, V.; Hoadley, S. T.; Cole, S. R.; Buttrill, C. S.; and Houck, J. A.: Design, Implementation, Simulation, and Testing of Digital Flutter Suppression Systems for the Active Flexible Wing Wind-Tunnel Model. Presented at the 17th Congress of the International Council of the Aeronautical Sciences, Stockholm, Sweden, September 9-14, 1990. ICAS Paper No. 90-1.3.2.
49. Pototzky, A. S.; Heeg, J.; and Perry, B., III: Computation of Maximum Gust Loads in Nonlinear Aircraft Using a New Method Based on the Matched Filter Approach and Numerical Optimization. Presented at the AIAA/ASME/ASCE/AHS/ASC 31st Structures, Structural Dynamics and Materials Conference, Long Beach, CA, April 2-4, 1990. Also available as NASA CP-3064, p. 221-230.
50. Pototzky, A. S.; Wieseman, C. D.; Hoadley, S. T.; and Mukhopadhyay, V.: Development and Testing of Methodology for Evaluating the Performance of Multi-Input/Multi-Output Digital Control Systems. Presented at the AIAA Guidance, Navigation, and Controls Conference, Portland, OR, August 20-22, 1990. AIAA Paper No. 90-3501. Also available as NASA TM-102704, July 1990.
51. Woods, J. A.; and Gilbert, M. G.: Direct Use of Linear Time-Domain Aerodynamics in Aeroservoelastic Analysis: Aerodynamic Model. Presented at the AIAA/ASME/ASCE/AHS/ASC 31st Structures, Structural Dynamics and Materials Conference, Long Beach, CA, April 2-4, 1990. Also available as NASA CP-3064.
52. Zeiler, T. A.; and Gilbert, M. G.: Integrated Control/Structure Optimization by Multilevel Decomposition. Presented at the AIAA Structures, Structural Dynamics and Materials Conference, Long Beach, CA, April 3-5, 1990. AIAA Paper 90-1057. Also available as NASA TM-102619, March 1990.

#### Technical Briefs:

53. Wieseman, C. D.: Methodology for Matching Experimental and Analytical Aerodynamic Data. NASA Tech Brief LAR-14244.

#### Technical Presentations:

54. Christhilf, D.; Adams, W.; Waszak, M.; Srinathkumar, S.; and Mukhopadhyay, V.: Design and Test of Three Active Flutter Suppression Controllers. Presented at the 4th Workshop on Computational Control of Flexible Aerospace Systems, Williamsburg, VA, July 11-13, 1990.
55. Gilbert, M. G.: Research in Aeroservoelasticity at NASA Langley Research Center. Aerospace Flutter and Dynamics Council Meeting, Orlando, FL, October 1989.
56. Gilbert, M. G.; Pototzky, A. S.; Heeg, J.; Dunn, H. J.; Spain, C. V.; and Soistmann, D. L.: Hypersonic Aeroelasticity Method Reduces Thermal Heating Effects on Flutter. Senior Management Research Review, NASA Langley Research Center, Hampton, VA, January 1990.
57. Hoadley, S. T.; Buttrill, C.; McGraw, S.; and Houck, J.: Development, Simulation, Validation, and Wind-Tunnel Testing of a Digital Controller System for Flutter Suppression. Presented at the 4th Workshop on Computational Control of Flexible Aerospace Systems, Williamsburg, VA, July 11-13, 1990.
58. Perry, B., III; and Pototzky, A. S.: Computation of Maximized and Time-Correlated Gust Loads Using Matched Filter Theory - A Review. Gust Specialists' Meeting, Long Beach, CA, April 6, 1990.
59. Pototzky, A. S.; Heeg, J.; and Perry, B., III: Computation of Maximum Gust Loads in Nonlinear Aircraft Using a New Method Based on the Matched Filter Approach and Numerical Optimization. Gust Specialists' Meeting, Long Beach, CA, April 6, 1990.
60. Pototzky, A. S.; Wieseman, C. D.; Hoadley, S. T.; and Mukhopadhyay, V.: The Development and Testing of a Methodology to Evaluate Controller Performance and Stability for Multi-Input and Multi-Output Digital Control Systems. Presented at the 4th Workshop on Computational Control of Flexible Aerospace Systems, Williamsburg, VA, July 11-13, 1990.
61. Silva, W. A.; Heeg, J.; and Bennett, R. M.: Aeroelastic Modeling of the Active Flexible Wing Wind-Tunnel Model. Presented at the 4th Workshop on Computational Control of Flexible Aerospace Systems, Williamsburg, VA, July 11-13, 1990.

#### Contractor Reports:

62. Dinyovszky P.; and Twomey W. J.: United Technologies Corporation, Sikorsky Aircraft Division, Stratford, CT: Plan, Formulate, and Discuss a NASTRAN Finite Element Model of the UH-60A Helicopter Airframe. NASA CR-181975, February 1990.
63. DiTaranto, R. A.; Snakewitsch, V.: Calculation of Fighter Vibration Levels of the AH-1G Helicopter and Correlation with Existing Flight Vibration Measurements. NASA CR-181923, November 1989.

64. Dompka, R. V.: Investigation of Difficult Component Effects on Finite Element Model Vibration Prediction for the Bell AH-1G Helicopter. NASA CR-181916, Vol. I and Vol. II, October 1989.
65. Ferg, D.; Foote, L.; Korkosz, G.; Straub, F.; Toossi, MI; Weisenburger, R.: Plan, Execute, and Discuss Vibration Measurements and Correlations to Evaluate a NASTRAN Finite Element Model of the AH-64 Helicopter Airframe. (NAS1-17498 McDonnell Douglas Helicopter Company.) NASA CR-181973, January 1990, 235 p.
66. Howland, G. R.; Durno, J. A.; and Twomey, W. J.: Ground Shake Test of the UH-60A Helicopter Airframe and Comparison With NASTRAN Finite Element Model Predictions. NASA CR-181993, Contract NAS1-17499, March 1990.
67. Sangha, K.; Shamie, J.: Correlation of AH-1G Airframe Flight Vibration Data With a Coupled Rotor-Fuselage Analysis. (NAS1-17498 McDonnell Douglas Helicopter Company.) NASA CR-181974, August 1990, 228 p.
68. Sopher, R.; Twomey, W. J.: Calculation of Flight Vibration Levels of the AH-1G Helicopter and Correlation With Existing Flight Vibration Measurements. (NAS1-17499 United Technologies Corporation, Sikorsky Aircraft Division.) NASA CR-182031, April 1990, 206 p.
69. Stebbins, R. F.; Twomey, W. J.: Plan, Formulate, and Discuss a NASTRAN Finite Element Model of the Sikorsky ACAP Helicopter Airframe. (NAS1-17499 United Technologies Corporation, Sikorsky Aircraft.) NASA CR-182059, June 1990, 240 p.
70. Sopher, R.; and Twomey, W. J.: Calculation of Flight Vibration Levels of the AH-1G Helicopter and Correlation With Existing Flight Vibration Measurements. NASA CR-182031, April 1990.

Textbook:

71. Mukhopadhyay, V.: Control Law Synthesis and Stability Robustness Improvement Using Constrained Optimization Techniques. Chapter published in textbook entitled Control and Dynamic Systems, Vol 32, Academic Press, Inc., 1990.

### **Landing and Impact Dynamics Branch**

Journal Publications:

72. Boitnott, Richard L.; and Fasanella, Edwin L.: Crashworthiness of Composite Floor Sections. Aerospace Engineering. The Society of Automotive Engineering, Inc. (SAE), December 1989, p. 9-12.
73. Noor, A. K.; Kim, K. O.; Tanner, J. A.: Analysis of Aircraft Tires Via Semianalytic Finite Elements. Finite Elements in Analysis and Design, Vol. 6, No. 3, March 1990, p. 217-233.

74. Noor, Ahmed K.; Kim, Kyun O.; and Tanner, John A.: Nonlinear Analysis of Aircraft Tires Via Semianalytic Finite Elements. Computational Mechanics of Nonlinear Response of Shells, edited by W. B. Kratzig and E. Onate, Springer-Verlag, Berlin, 1990, p. 327-347.
75. Yager, Thomas J.: Friction Measurements Under Winter Runway Conditions. Aerospace Engineering, The Society of Automotive Engineering, Inc. (SAE), February 1990, p 32-35.

#### Formal NASA Reports:

76. Fasanella, Edwin L.; and Robinson, Martha P.: Analysis of the National Transonic Facility Mishap. NASA TM-101686, January 1990.
77. Fasanella, Edwin L.; Carden, Huey D.; Boitnott, Richard L.; and Hayduk, Robert J.: A Review of the Analytical Simulation of Aircraft Crash Dynamics. NASA TM-102595, January 1990.
78. Jackson, Karen E.: Scaling Effects in the Static and Dynamic Response of Graphite-Epoxy Beam-Columns. NASA TM-102697, July 1990.
79. Jones, L. E.; and Carden, H. D.: Evaluation of Energy Absorption of New Concepts of Aircraft Composite Subfloor Intersections. NASA TP-2951, November 1989.
80. Kim, K. O.; Noor, A. K.; and Tanner, J. A.: Modeling and Analysis of the Space Shuttle Nose-Gear Tire with Semianalytic Finite Elements. NASA TP-2977, April 1990, 34 p.
81. Yager, T. J.; Vogler, W. A.; and Baldasare, P.: Evaluation of Two Transport Aircraft and Several Ground Test Vehicle Friction Measurements Obtained for Various Runway Surface Types and Conditions - A Summary of Test Results From Joint FAA/NASA Runway Friction Program. NASA TP-2917, February 1990, 300 p.

#### Conference Presentations:

82. Carden, Huey D.: Unique Failure Behavior of Metal/Composite Aircraft Structural Components Under Crash Type Loads. Presented at the 1990 Aircraft Interiors Conference, Wichita, KS, April 24-25, 1990. In Proceedings.
83. Carden, H. D.; Boitnott, R. L.; and Fasanella, E. L.: Behavior of Composite/Metal Aircraft Structural Elements and Components Under Crash Type Loads--What are They Telling Us? Presented at the 17th Congress of the International Council of Aeronautical Sciences (ICAS), Stockholm, Sweden, September 9-14, 1990. ICAS Paper No. 90-1.7.1. Also available as NASA TM-102681 and as USAAVSCOM TR-90-B-003, May 1990, 15 p.
84. Carden, H. D.; Noor, A. K.; and Peters, J. M.: Free Vibrations of Thin-Walled Semicircular Graphite-Epoxy Composite Frames. Presented at the 17th Congress of the International Council of Aeronautical Sciences (ICAS), Stockholm, Sweden,



September 9-14, 1990. ICAS Paper No. 90-1.7.4. Also available as NASA TM-102680, May 1990, 16 p.

85. Yager, Thomas J.: Aircraft Radial-Ply Tire Friction Performance. Presented at the 1989 Clemson University Tire Industry Conference, Greenville, SC, October 25-26, 1989. In proceedings.

#### Technical Briefs:

86. Daugherty, Robert H.; and Stubbs, Sandy M.: Measurement of Water Sprays Generated by Airplane Tires. NASA Tech Brief LAR-14030.
87. Davis, P. A.; Stubbs, S. M.; and Tanner, J. A.: Langley Aircraft Landing Dynamics Facility. NASA Tech Brief LAR-14038.

#### Textbooks:

88. Tanner, John A.; Editor: Aircraft Landing Gear Systems. SAE PT-37, ISBN 1-56091-074-7, 1990.

### **Spacecraft Dynamics Branch**

#### Journal Publications:

89. Belvin, W. K.; Park, K. C.: Structural Tailoring and Feedback Control Synthesis: An Interdisciplinary Approach. Journal of Guidance, Control, and Dynamics, Vol. 13, No. 3, May/June 1990, p. 424-429.
90. Hanks, Brantley R.: Controls Structures Interaction, An Interdisciplinary Challenge for Large Spacecraft. Advances in the Astronautical Sciences, Vol. 70, April 1990.
91. Juang, J-N; and Maghami, P. G.: Robust Eigensystem Assignment for Second Order Dynamics System. Mechanics and Control of Large Space Structures edited by John L. Junkins. AIAA Monograph on Progress in Astronautics and Aeronautics, Vol. 29, 1990, p. 373-387.
92. Juang, J. N.; Horta, L. G.; and Longman, R. W.: Input/Output System Identification: Learning From Repeated Experiments, Mechanics and Control of Large Space Structures edited by John L. Junkins. AIAA Monograph on Progress in Astronautics and Aeronautics, Vol. 29, 1990, p. 87-99.
93. Maghami, P. G.; and Juang, J-N.: A Controller Design for Multi-Body Large Angle Maneuvers. Mechanics of Structures and Machines, Vol. 17, No. 1, 1989, p. 33-52.
94. Pappa, R. S.: Identification Challenges for Large Space Structures, Sound and Vibration, April 1990, p. 16-21.

95. Williams, T.; and Juang, J. N.: Pole/Zero Cancellations in Flexible Space Structures, Journal of Guidance, Control and Dynamics, Vol. 13, No. 4, July/August 1990, p. 684-690.

Formal NASA Reports:

96. Juang, J. N.; and Phan, M.: Robust Controller Designs for Second-Order Dynamic Systems: A Virtual Passive Approach. NASA TM-102666, May 1990.
97. Juang, J-N; and Lew, J-S: Integration of System Identification and Robust Controller Designs for Flexible Structures in Space. NASA TM-102695, July 1990.
98. Juang, J-N.; and Maghami, P. G.: Robust Eigensystem Assignment for State Estimators Using Second-Order Models. NASA TM-102696, July 1990.
99. McGowan, P. E.; Edighoffer, H. H.; and Wallace, J. W.: Development of an Experimental Space Station Scale Model for Structural Dynamics Research. NASA TM-102601, January 1990.
100. Stockwell, A. E.; Perez, S. E.; and Pappa, R. S.: Integrated Modeling and Analysis of a Space-Based Truss Test Component. NASA TM-102615, March 1990.

Conference Presentations:

101. Ayers, J. K.; Lim, T. W.; and Cooper, P. A.: Dynamic Characteristics of the Space Station Freedom Mars Evolution Reference Configuration. Presented at the AIAA 28th Aerospace Science Meeting and Exhibit, Reno, NV, January 8-11, 1990. AIAA Paper No. 90-0746-CP.
102. Belvin, W. K.; and Park, K. C.: Computer Implementation of Analysis and Optimization Procedures for Control-Structures Interaction Problems. Presented at the AIAA Dynamics Specialists Conference, Long Beach, CA, April 5-6, 1990. AIAA Paper No. 90-1194-CP.
103. Bergmann, M.; Longman, R. W.; and Juang, J. N.: Variance and Bias Computation for Enhanced System Identification. Presented at the 28th IEEE Conference on Decision and Control, Tampa, FL, December 13-15, 1989. Also available in the conference proceedings in Vol. 1, p. 155-161.
104. Bergmann, M.; Longman, R. W.; and Juang, J-N.: Optimization of Actuator and Sensor Placement for On-Orbit Identification in Large Flexible Spacecraft. Presented at the AIAA Guidance, Navigation, and Control Conference, Portland, OR, August 1990, p. 1785-1793. AIAA Paper No. 90-3516-CP.
105. Chen, C. W.; Huang, J-K.; Phan, M.; and Juang, J-N.: Integrated System Identification and Modal State Estimation for Control of Large Flexible Space Structures. Proceedings of the AIAA Guidance, Navigation, and Control Conference, Portland, OR, August 1990, p. 1396-1404. AIAA Paper No. 90-3470-CP.

- 106 Chew, M-S.; Juang, J-N.; and Yang, L-F.: A Novel Suspension Design for Ground Testing of Large Space Structures. Proceedings of the ASME Design Technical Conference, Chicago, IL, September 16-19, 1990. To appear in the Journal of Mechanism, Transmissions, and Automation in Design.
107. Cooley, V. M.; and Woodard, S. E.: Suspension Research at the Langley Research Center. Presented at the Workshop on Micro-Gravity Simulation in Ground Validation Testing of Large Space Structures, Denver CO, November 1-2, 1989. In the October 1990 proceedings as Paper No. 6-2.1.
- 108 Cooper, P. A.; and Ayers, J. K.: Structural Dynamics and Control Considerations for Space Station Transportation Node Concepts. Presented at the First Symposium on the Evolution of Space Station Freedom, League City, TX, February 6-8, 1990. Proceedings pending.
109. Cooper, P. A.; Martinovic, Z. N.; and Lim, T. W.: Control/Structures Interaction Considerations for Space Station Transportation Node Concepts. Presented at the NASA OAET Workshop on Technology for Space Station Evolution, Dallas, TX, January 16-19, 1990. Proceedings pending.
110. Cooper, P. A.; Johnson, J. W.; and McGowan, P. E.: The Space Station Structural Characterization Experiment - An Update. Presented at the Second USAF/NASA Workshop on System Identification and Health Monitoring of Precision Space Structures, Pasadena, CA, March 27-29, 1990. Proceedings pending.
111. Housner, J. M.; Pappa, R. S.; and Perez, S. E.: Flexible Spacecraft Control Research on the Mini-Mast Ground Test Facility. Presented at the AIAA Aerospace Engineering Conference and Show, Los Angeles, CA, February 13-15, 1990.
112. Juang, J. N.; Horta, L. G.; Phan, M.; and Longman, R. W.: Learning System Identification for Flexible Structures. Presented at the Second USAF/NASA Workshop on System Identification and Health Monitoring of Precision Space Structures, California Institute of Technology, Pasadena, CA, March 1990. Proceedings pending.
113. Juang, J. N.; Horta, L. G.; Phan, M.; and Longman, R. W.: Identification of Flexible Structures Using System Realization Methods. Presented at the AIAA Dynamics Specialists Conference, Long Beach, CA, April 5-6, 1990. In proceedings Vol. 1, AIAA Paper No. 90-1209-CP.
114. Juang, J-N; and Maghami, P. G.: Robust Eigensystem Assignment for Second Order Dynamics System. Presented at the AIAA Dynamics Specialist Conference, Long Beach, CA, April 5-6, 1990. In proceedings Vol. 1, AIAA Paper No. 90-1191-CP.
115. Juang, J-N; and Lew, J-S: Integration of System Identification and Robust Controller Designs for Flexible Structures in Space. Presented at the AIAA Guidance, Navigation, and Control Conference, Portland, OR, August 20-22, 1990, p. 1361-1375. AIAA Paper No. 90-3467-CP.

116. Juang, J-N.; and Maghami, P. G.: Robust Eigensystem Assignment for State Estimators Using Second-Order Models. Presented at the AIAA Guidance, Navigation and Control Conference, Portland, OR, August 20-22, 1990. In proceedings Vol. 2, AIAA Paper No. 90-3474-CP.
117. Kaszubowski, M. J.; Martinovic, Z. N.; and Cooper, P. A.: Structural Dynamic Characteristics of the Space Station Freedom First Assembly Flight Concept. Presented at the 28th Aerospace Sciences Meeting and Exhibit, Reno, NV, January 8-11, 1990. AIAA Paper No. 90-0748.
118. Lim, K. B.; and Horta, L. G.: A Line-of-Sight Performance Criteria for Controller Design of Proposed CSI Model. Presented at the AIAA Dynamics Specialist Conference, Long Beach, CA, April 5-6, 1990. AIAA Paper No. 90-1226-CP.
119. Lim, T. W.; and Cooper, P. A.: Control/Structure Interaction Study of the Space Station Freedom First Flight Concept During Reboost. Presented at the AIAA 28th Aerospace Sciences Meeting and Exhibit, Reno, NV, January 8-11, 1990. AIAA Paper No. 90-0747.
120. McGowan, P. E.; Edighoffer, H. H.; and Wallace, J. W.: Development of an Experimental Space Station Scale Model for Structural Dynamics Research. Presented at the 60th Shock and Vibration Symposium, Virginia Beach, VA, November 14-16, 1989. In proceedings Vol. 2, p. 13-29. Also available as NASA TM-102601, January 1990, 18 p.
121. McGowan, P. E.; and Housner, J. M.: Dynamic Scale Model Technology and Its Relation to Evolutionary Space Station Technology. Presented at the Technology for Space Station Workshop, Dallas, TX, January 16-19, 1990. Proceedings pending.
122. McGowan, Paul E.; Smith, Suzanne W.; and Javeed, Mehzad: Experiments For Locating Damaged Members In a Truss Structure. Presented at the Second USAF/NASA Workshop System Identification and Health Monitoring of Precision Space Structures, Pasadena, CA, March 27-29, 1990. Proceedings pending.
123. Pappa, R. S.; and Perez, S. E.: CSI Testbeds at NASA Langley: Mini-Mast and Evolutionary Models. Presented at the Workshop on Computational Techniques in Identification and Control of Flexible Flight Structures, Lake Arrowhead, CA, November 2-4, 1989. Proceedings pending.
124. Pappa, R. S.: Identification Challenges for Large Space Structures. Keynote Address. Presented at the 8th International Modal Analysis Conference and Exhibit, Kissimmee, FL, January 29 - February 1, 1990. In proceedings, Vol. I, p. xv--xxiii.
125. Pappa, R. S.; Schenk, A.; and Noll, C.: ERA Modal Identification Experiences with Mini-Mast. Presented at the Second USAF/NASA Workshop on System Identification and Health Monitoring of Precision Space Structures, Pasadena, CA, March 27-29, 1990. Proceedings pending.

126. Phan, M.; Juang, J. N.; and Longman, R. W.: Recent Developments in Learning Control and System Identification for Robots and Structures. Presented at the International Conference on Dynamics of Flexible Structures in Space, Cranfield, United Kingdom, May 15-18, 1990.
127. Phan, M.; Longman, R. W.; and Juang, J-N.: Indirect Repetitive Control for Linear Discrete Multivariable Systems. Presented at the 27th Annual Allerton Conference on Communication, Control, and Computing, Monticello, IL, September 1990. Proceedings pending.
128. Schenk, A.; and Pappa, R. S.: Modal Identification of a Deployable Space Truss. Presented at the 15th International Seminar on Modal Analysis and Structural Dynamics. Katholieke Universiteit Leuven; Leuven, Belgium, September 17-21, 1990.
129. Stockwell, A. E.; Perez, S. E.; and Pappa, R. S.: Integrated Modeling and Analysis of a Space-Based Truss Test Component. Presented at the MacNeal-Schwendler (MSC) World Users Conference, Los Angeles, CA, March 26-30, 1990. In proceedings, Paper No. 16. Also available as NASA TM-102615, March 1990, 27 p.
130. Sulla, J. L.; Juang, J-N.; and Horta, L. G.: Analysis and Application of a Velocity Command Motor as a Reaction Mass Actuator. Presented at the AIAA Dynamics Specialist Conference, Long Beach, CA, April 5-6, 1990. In proceedings p. 360-370. AIAA Paper No. 90-1227-CP.
131. Wie, B.; Horta, L. G.; Sulla, J. L.: Active Structural Control Design and Experiments for the Mini-Mast. Presented at the AIAA Guidance, Navigation, and Control Conference, Portland, OR, August 20-22, 1990.

#### Technical Briefs:

132. Belvin, W. K.: Modeling of Joints for the Dynamic Analysis of Truss Structures. NASA Tech Brief LAR-14306.
133. Chew, M-S.; Yang, L-F. (Old Dominion University); and Juang, J-N (Langley Research Center): Suspension Device for Low-Frequency Structures. NASA Tech Brief LAR-14272.
134. Woodard, S. E.; and Cooley, V. M.: Zero-Spring-Rate Mechanism/Air Suspension Cart. NASA Tech Brief LAR-14142.

### **Interdisciplinary Research Office**

#### Journal Publications:

135. Chattopadhyay, Aditi; and Walsh, Joanne L.: Application of Optimization Methods to Helicopter Rotor Blade Design. Structural Optimization, Vol. 2, 1990, p. 11-22.

136. Chattopadhyay, Aditi; and Walsh, Joanne L.: Minimum Weight Design of Rotor Blades with Multiple Frequency and Stress Constraints. Technical Note. AIAA Journal, Vol. 28, No. 3, March 1990, p. 565-567.
137. Chattopadhyay, Aditi; and Walsh, Joanne L.: Minimum Weight Design of Helicopter Rotor Blades with Frequency Constraints. Technical Note. Journal of American Helicopter Society, October 1989, Vol. 34, No. 4.
138. Fadel, G. M.; Riley, M. F.; and Barthelemy, J-F, M.: Two Point Exponential Approximation Method for Structural Optimization. Structural Optimization, Vol. 2, 1990, p. 117-124.
139. Haftka, Raphael T.; and Adelman, Howard M.: Recent Developments in Structural Sensitivity Analysis. Structural Optimization, Vol. 1, 1989, p. 137-151.
140. Pritchard, Jocelyn I.; and Adelman, Howard M.: Optimal Placement of Turning Masses for Vibration Reduction in Helicopter Rotor Blades AIAA Journal, Vol. 28, No. 2, February 1990, p. 309-315.
141. Rogers, James L.: Knowledge-Based Tool for Decomposing Complex Design Problems. Journal of Computing in Civil Engineering, Vol. 4, No. 4, October 1990, p. 298-312.
142. Sobieszczanski-Sobieski, J.: Sensitivity of Complex, Internally Coupled Systems, AIAA Journal, Vol. 28, No. 1, January 1990, p. 153-160.
143. Sobieszczanski-Sobieski, J.: Higher Order Sensitivity Analysis of Complex, Coupled Systems. AIAA Journal, Vol. 28, No. 4, April 1990, p. 736.
144. Yates, E. Carson, Jr.: AGARD Standard Aeroelastic Configurations for Dynamic Response. I-Wing 445.6. North Atlantic Treaty Organization Advisory Group For Aerospace Research and Development. AGARD Report No. 765, 1989.
145. Yates, E. C., Jr.: Integral-Equation Methods in Steady and Unsteady Subsonic, Transonic and Supersonic Aerodynamics for Interdisciplinary Design. NASA TM-102677, May 1990, 16 p.

#### Formal NASA Reports:

146. Adelman, Howard M.; and Mantay, Wayne R.: Integrated Multidisciplinary Optimization of Rotorcraft: A Plan for Development. NASA TM-101617, 1989.
147. Kao, Pi-Jen; Wrenn, Gregory A.; and Giles, Gary L.: Comparison of Equivalent Plate and Finite Element Analysis of a Realistic Aircraft Structural Configuration. AIAA/AHS/ASEE Aircraft Design, Systems and Operations Conference, Dayton, OH, AIAA Paper No. 90-3293, September 1990.

148. Logan, T.; Sobieszczanski-Sobieski, J.; and Abdi, Frank: Optimization of Aircraft Configurations in Multidisciplinary Environment. Proceedings of 17th Congress of the International Council of Aeronautical Sciences (ICAS90), Stockholm, Sweden, September 1990.
149. Pritchard, J. I.; and Adelman, H. M.: Differential Equation Based Method for Accurate Approximations in Optimization. NASA TM-102639, AVSCOM TM-90-B-006, April 1990, 12 p.
150. Sobieszczanski-Sobieski, J.; Grossman, B.; Haftka, R. T.; Kao, O.; Polen, D.; and Rais, Rohani M.: Integrated Aerodynamic-Structural Design of a Transport Wing, AIAA Paper No. 89-2129.
151. Sobieszczanski-Sobieski, Jaroslaw: Overcoming the Bellman's "Curse of Dimensionality" in Large Optimization Problems. NASA TM-102662, April 1990.
152. Sobieszczanski-Sobieski, Jaroslaw: Approximate Simulation Model for Analysis and Optimization in Engineering System Design. Published in proceedings of ISAOC '89 (July 1989). NASA TM-101616, April 1990.

#### Conference Presentations:

153. Adelman, Howard M.: Integration of Structural Mechanics, Aerodynamics and Performance in Optimization of Rotorcraft. Presented at the 1990 AIAA Aerospace Engineering Conference and Show, Los Angeles, CA, February 13-15, 1990.
154. Barthelemy, J-F.: Sensitivity Analysis of a Wing Aeroelastic Response. Presented at the 17th Congress of the International Council of Aeronautical Sciences (ICAS), Stockholm, Sweden, September 9-14, 1990.
155. Barthelemy, Jean-Francois; and Noor, Ahmed K., (Editors): Research in Structures, Structural Dynamics and Materials-1990 SDM Conference. Publication of work in progress - April 2-4, 1990, Long Beach, CA. NASA CP-3064, April 1990.
156. Barthelemy, Jean-Francois M.; Coen, Peter G.; Wrenn, Gregory A.; and Riley, Michael F.: Application of Multidisciplinary Optimization Methods to the Design of a Supersonic Transport. Third Air Force/NASA Symposium on Recent Advances in Multidisciplinary Analysis and Optimization, San Francisco, CA, September 24-26, 1990.
157. Chattopadhyay, A.; and Jones, H. E.: Performance of an Optimized Rotor Blade at Off-Design Flight Conditions. Presented at the AHS/NASA Vertical Lift Aircraft Design Conference, January 16-19, 1990, San Francisco, CA. In Proceedings, Session No. 5.
158. Consoli, Robert Davis; and Sobieszczanski-Sobieski, Jaroslaw: Application of Advanced Multidisciplinary Analysis and Optimization Methods to Vehicle Design Synthesis. ICAS90, Stockholm, Sweden, September 9-14, 1990.

159. Fadel, G. M.; Riley, M. F.; and Barthelemy, J-F M.: Improved First-Order Approximation Method for Structural Optimization. Presented at 31st AIAA/ASME/ASCE/ASC/AHS Structures, Structural Dynamics and Materials Conference, Long Beach, CA, April 2-4, 1990. AIAA-90-1178-CP, p. 436-443.
160. Giles, Gary L.; and Norwood, R. Keith: Coupled Finite Element and Equivalent Plate Analysis of Aircraft Structures. Third Air Force/NASA Symposium on Recent Advances in Multidisciplinary Analysis and Optimization, San Francisco, CA, September 24-26, 1990.
161. Graves, P.; James, B.; and Padula, S.: Behavior Sensitivities for a Flexible Spacecraft with Non-Negligible Actuator Mass. Presented at Third Air Force/NASA Symposium on Recent Advances in Multidisciplinary Analysis and Optimization, San Francisco, CA, September 24-26, 1990.
162. Hajela, Prabhat; Bloebaum, Christina; and Sobieszczanski-Sobieski, Jaroslaw: Heuristic Decomposition in Multidisciplinary Optimization of Aircraft. International Council of Aeronautical Sciences Congress (ICAS90), Stockholm, Sweden, September 9-14, 1990.
163. Kao, Pi-Jin; Wrenn, Gregory A.; and Giles, Gary L.: Comparison of Equivalent Plate and Finite Element Analysis of a Realistic Aircraft Structural Configuration. Presented at AIAA/AHS/ASCE Aircraft Design, Systems and Operations Conference, Dayton, OH, September 17-19, 1990.
164. Kincaid, Rex K.; and Padula, Sharon L.: Minimizing Distortion and Internal Forces in Truss Structures by Simulated Annealing. Presented at 31st AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Long Beach, CA, April 2-4, 1990.
165. Logan, Trent; and Sobieszczanski-Sobieski, Jaroslaw: Optimization of Aircraft Configurations in Multidisciplinary Environment. International Council of Aeronautical Sciences Congress (ICAS90), Stockholm, Sweden, September 9-14, 1990.
166. Mantay, Wayne; and Adelman, Howard M.: Status of Integrated Multidisciplinary Rotorcraft Optimization Research at the Langley Research Center. Presented at the 46th AHS Annual Forum and Technology Display, Washington, D.C., May 21-23, 1990.
167. Padula, Sharon L.; and Polignone, Debra A.: New Evidence Favoring Multilevel Decomposition and Optimization. Third Air Force/NASA Symposium on Recent Advances in Multidisciplinary Analysis and Optimization, San Francisco, CA, September 24-26, 1990.
168. Padula, S. L.; Sandridge, C. A.; Walsh, J. L.; and Haftka, R. T.: Integrated Controls/Structures Optimization of a Large Space Structure. Presented at the 31st AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Long Beach, CA., April 2-4, 1990.



169. Pritchard, Jocelyn I.; and Adelman, Howard M.: Differential Equation Based Method for Accurate Approximations in Optimization. Presented at 31st Structures, Structural Dynamics and Materials Conference, Long Beach, CA, April 2-4, 1990.
170. Rogers, James L.: Decomposing a Complex Design Problem Using CLIPS. Presented at First CLIPS Conference, Houston, TX, August 13-15, 1990. Published in Proceedings.
171. Rogers, James L.; and Padula, Sharon L.: A Knowledge-Based Tool for the Decomposition of a Complex Analysis Problem. Presented at the Third Air Force/NASA Symposium on Recent Advances in Multidisciplinary Analysis and Optimization, San Francisco, CA, September 24-26, 1990. Published in Proceedings.
172. Rogers, James L.: The Potential Application of the Blackboard Model of Problem Solving to Multidisciplinary Design. Proceedings of the Seventh AIAA Computers in Aerospace Conference, Monterey, CA, October 1989, p. 686-695. Also available as NASA TM-101633.
173. Sobieszczanski-Sobieski, Jaroslaw: Everything Influences Everything Else: A Math That Can Help. Keynote address at 31st AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Long Beach, CA, April 2-4, 1990.
174. Sobieszczanski-Sobieski, Jaroslaw; and Morris, Alan: Integrated Analysis and Optimization Status Report. Presented at the 69th SMP Panel Meeting, Brussels, Belgium, October 2-6, 1989.
175. Sobieszczanski-Sobieski, Jaroslaw: Interdisciplinary Aerospace Applications of Design Optimization. First Annual Symposium on Mechanical System Design in Concurrent Engineering Environment, Iowa City, IA, October 24-25, 1989.
176. Walsh, Joanne L.: Performance Optimization of Helicopter Rotor Blades. Presented at AGARD's Special Course on Aerodynamics of Rotorcraft. NASA Ames Research Center, Moffett Field, CA, May 14-17, 1990.
177. Walsh, Joanne L.: Performance Optimization of Helicopter Rotor Blades. Presented at the Third Air Force/NASA Symposium on Recent Advances in Multidisciplinary Analysis and Optimization, San Francisco, CA, September 24-26, 1990.
178. Woodard, S.; Padula, S.; Graves, P.; and James, B.: A Multidisciplinary Approach to Optimization of Controlled Space Structures. Presented at Third Air Force/NASA Symposium on Recent Advances in Multidisciplinary Analysis and Optimization, San Francisco, CA, September 24-26, 1990.
179. Yates, E. Carson, Jr.; and Desmarais, Robert N.: Boundary-Integral Method for Calculating Aerodynamic Sensitivities with Illustration for Lifting-Surface Theory. Invited paper presented at Third International Congress of Fluid Mechanics, Cairo, Egypt, January 2-4, 1990. Published in the Proceedings.

180. Yates, E. Carson, Jr.; and Desmarais, Robert N.: Calculation of Aerodynamic Sensitivities by Boundary-Integral Methods and Application to Lifting-Surface Theory. Presented at the International Symposium on Boundary Element Methods (ISBEM 89), Hartford, CT, October 2-4, 1989. Proceedings published by Springer Verlag, 1989.

#### Technical Presentations:

181. Giles, Gary L.: Computational Structural Mechanics. Presented at the SMD State-of-the-Division Meeting, NASA Langley Research Center, Hampton, VA, February 28, 1990.

#### Technical Briefs:

182. Padula, S. L.; and Sobieski, J.: A Computer Simulation for Multilevel Optimization of Design. NASA Technical Brief, LAR-13850, April 1990.

#### Contractor Reports

183. Chattopadhyay, A.: Performance of an Optimized Rotor Blade at Off-Design Flight Conditions. (NAS1-18599 Analytical Services & Materials, Inc.) NASA CR-4288, March 1990, 16 p.
184. Haftka, R. T.: Screening Actuator Locations for Static Shape Control. (NAG1-224 Virginia Polytechnic Institute and State University.) NASA CR-181970, January 1990, 18 p.
185. Hollowell, S. J.; Beeman, E. R., II; and Hiyama, R. M.: Conceptual Design Optimization Study. (NAS1-18015 Rockwell International Corporation.) NASA CR-4298, May 1990, 124 p.
186. Wrenn, G. A.; and Dovi, A. R.: Multilevel Decomposition Approach to the Preliminary Sizing of a Transport Aircraft Wing. (NAS1-19000 Lockheed Engineering & Sciences Company.) NASA CR-4296, May 1990, 36 p.

## **F.Y. 1991 PLANS**

The F.Y. 1991 plans for the Structural Dynamics Division are broken out by each of the branches (technical areas) and selected highlights of proposed F.Y. 1991 milestones are presented.

### **Configuration Aeroelasticity Branch**

Figure 82 summarizes accomplishments planned for F.Y. 1991 selected from the Branch's broad based research program on dynamic and aeroelastic phenomena of aircraft and rotorcraft. A large portion of this work is associated with wind tunnel tests in the Langley TDT with companion theoretical studies. Research studies are planned for both rotorcraft and aircraft. Wind tunnel testing will be limited to the first half of F.Y. 1991 prior to shutdown of the TDT for construction work associated with the CofF project "Modifications to the Heavy Gas Reclamation System for the TDT."

Testing related to aircraft aeroelasticity will include the second test of the Active Flexible Wing (AFW) model with new active control concepts for roll control and for flutter suppression. The roll control and the flutter suppression control laws will be tested first individually and then simultaneously. The AFW test is part of a NASA/Rockwell cooperative program.

Basic studies under the Benchmark Models Program will include the second test of the NACA 0012 rectangular wing on a flexible mount to provide additional wing surface unsteady pressure measurements to supplement flutter boundary and other instability data already acquired. Two similar basic studies models will be fabricated, instrumented and checked out in the laboratory during F.Y. 1991, one with a supercritical airfoil and the other with the same NACA 0012 airfoil but with the addition of a trailing edge control surface and separate upper and lower surface spoilers all of which are to be used in the evaluation of active control laws for flutter suppression.

The rotorcraft aeroelasticity work will include initial testing of 2 second generation Aeroelastic Rotor Experimental System (ARES) testbed systems that improve the capability to model the interaction between the helicopter rotor and the body. The first, ARES 1.5, will be used for a rotor test in the TDT and the second, ARES 2.0, will be tested in the Hover Facility. The ARES 1.5 mounts the metric section of the ARES model on a static gimbal or "soft mount." This mount will allow the model fixed system stiffness and damping characteristics in both pitch and roll to be adjusted. The ARES 2.0 mounts the metric section of the ARES on a platform which is supported by six hydraulic actuators. These actuators will be computer controlled to obtain the desired body roll, pitch, yaw, side, normal and axial motions.

Highlights of proposed F.Y. 1991 research for the three technical areas of Aircraft Aeroelasticity, Rotorcraft Aeroelasticity, and Benchmark Models are shown in figures 83 through 85, respectively.

### Unsteady Aerodynamics Branch

For F.Y. 1991 there will be continuing activity in developing computational methods to solve nonlinear, unsteady fluid flow equations for application to aeroelastic analysis (fig. 86). There will be continued applications of the CAP-TSD code to aeroelastic response problems in order to further define its range of accuracy. As part of this activity, the branch will continue to provide support for the CAP-TSD code via a contract programmer. In addition, unsteady aerodynamic and aeroelastic response calculations will be performed using higher-order methods, such as solution procedures based on the Euler and Navier-Stokes equations. Correlations of computed results from UAB developed Euler/Navier-Stokes codes with other theoretical solutions and experimental data will help to evaluate and validate the new CFD methods (fig. 87(a)). This year will also see new developments in the prediction of vortex and viscous dominated flows (see figure 88) and their roles in aeroelastic response phenomena. These research efforts with higher-order CFD methods will be carried out using both structured and unstructured grid flow solvers. Finally, a new initiative in F.Y. 1991 will be the development of an in-house capability to generate computational grids for use with both structured and unstructured grid CFD procedures.

### Aeroservoelasticity Branch

Figure 89 lists the major tasks being pursued by the Aeroservoelasticity Branch in F.Y. 1991. In the Design Methodology area, activities to design low-order, MIMO, robust digital control laws for flutter suppression and for rolling maneuver load alleviation will be continued. These control laws will be tested separately and in combination on the AFW wind tunnel model during the spring of 1991 to obtain data for validating advanced design codes. The development of an integrated multidisciplinary design approach based on hierarchical multilevel decomposition, optimization techniques, and sensitivity information will be continued as part of the HiSAIR (High-Speed Airframe Integration Research) Project. The branch objectives in this effort are to include aeroelasticity and ASE in the preliminary design activity of flight vehicles. Investigations will continue in evaluating the feasibility of employing adaptive structures technology for aeroelastic and ASE application through simple wind tunnel demonstrations. In the Analysis Methodology and Applications area, the focus of attention involves the development of procedures for using nonlinear transonic aerodynamics to improve our ASE analysis and design methodologies. Studies to assess the effects of high temperatures and thermal gradients on the aeroelastic and ASE characteristics of the NASP vehicle will be initiated. Various active control and passive concepts which offer the potential for improving the loss of aircraft stability or performance due to thermal effects will be investigated. In the area of Rotorcraft Structural Dynamics, research is continuing in the development of advanced finite element modeling techniques to improve the prediction of rotorcraft airframe vibrations. In addition, studies will continue in the areas of coupled rotor-airframe systems, airframe structural optimization under dynamics constraints, and extension-twist coupling for passively controlling blade twist for improving the aerodynamic performance of tiltrotor aircraft.

Selected highlights of ongoing F.Y. 1991 research are shown in figures 90 through 95.

### Landing and Impact Dynamics Branch

Figure 96 lists the areas of continuing activity in the landing dynamics side of the branch for F.Y. 1991. The activities include development of a research plan and initiation of the Advanced Active Control Landing Gear Program. The research plan will be based, in part, on feedback from an Active Control Landing Gear Workshop scheduled for April 1991. Phase II Heavy Rain Simulation testing on ALDF will be completed in F.Y. 1991 and the wing will be removed from the carriage. Phase I testing of the 26 x 6.6 bias-ply and radial-belted aircraft tires on smooth, ungrooved concrete surfaces will be completed in this time frame, and initial tests to define the normal and friction force distribution in the footprints of rolling tires will be conducted on ALDF. The initial version of the National Tire Modeling Code will be distributed to industry and efforts will continue to develop computationally efficient algorithms for tire modeling. These experimental and analytical programs will develop the landing gear technology necessary for safe ground handling operations for future aircraft such as the HSCT.

Figure 97 lists the areas of continuing activity in the impact dynamics group for F.Y. 1991. The ongoing composite scaling studies will be extended to investigate the various failure mechanisms exhibited by composite structures. Efforts will continue to enhance the family of nonlinear shell and beam composite elements in the DYCAST computer code. Various static and dynamic tests will be conducted to evaluate the effect of floor location on the response characteristics of composite fuselage frame concepts subjected to crash loads. Composite subfloor components for full-scale GA composite airframes will be designed in F.Y. 1991 and the airframes will eventually be used as crash test specimens. At the same time static and dynamic testing will continue on I-, J-, and C-shaped fuselage concepts. Finally, the effort to develop and enhance computationally efficient algorithms for composite structural analysis will continue.

### Spacecraft Dynamics Branch

During F.Y. 1991, as in F.Y. 1990, two major areas of focused technology development will be emphasized in addition to base research and technology development. The first focused technology area is the control of flexible spacecraft under the Controls Structures Interaction (CSI) Program. Focusing on ground test methods, system-level experimental studies will continue on a 55-foot-long space platform simulator model, the CSI Evolutionary Model, which is expected to evolve in complexity over a period of years. For F.Y. 1991 these experiments will emphasize line-of-sight control studies using a 15-thruster pneumatic-jet control system and advanced digital model-in-the-loop control algorithms. Fabrication of the next phase of hardware components, to demonstrate improved integrated structure-control design compatibility, will begin and advanced electro-mechanical actuators will be designed. A second structure, the 20-meter-long Mini-Mast will continue, for the first half-year, to serve as a focus for evaluating flexible spacecraft control algorithms developed by guest investigators from three universities and then be phased out of use. A third CSI activity will be to participate in the simulation and evaluation of candidate experiments for on-orbit CSI technology development, including a proposed demonstration using the Space Shuttle Remote Manipulator System.

The second major area of focused technology development, structural dynamics analysis and test methods, will emphasize system identification and test methods for space structures which cannot be accurately tested for dynamic behavior in Earth gravity. Because of its large size and expected flight schedule, the Space Station Freedom will continue to be used as a focus spacecraft in the expectation that methods developed can ultimately be verified using on-orbit data. A test and analysis program based on a 1/10th-size, 1/5th-frequency, hybrid-scale model of the circa-1990 SSF configuration will emphasize evaluation of modal superposition analysis and component substructure test methods. Development of an on-orbit dynamics measurement plan in support of the Modal Identification Experiment (MIE) Project will continue, emphasizing data analysis requirements and difficulties. In both of these activities which focus on Space Station Freedom, requirements for adjustment of plans and rework of completed items which may result from pending SSF design changes will be evaluated.

In base research and technology, three areas of research will be emphasized. The important problem of predicting and controlling the behavior of multiple flexible bodies undergoing large maneuvers will continue to be studied and a simple articulated, multi-body, phenomena-simulator experimental model will be fabricated. System identification will continue to be a research area with experimental evaluation of algorithms which learn in repeated tests being emphasized. A study of advanced computational methods for model-based control, where the model includes significant structural flexibility will be initiated.

#### Interdisciplinary Research Office

During F.Y. 1991 the emphasis of the research will be on applying and validating integrated multidisciplinary optimization methods for three applications: high speed aircraft, rotorcraft, and control structure integrated optimization of spacecraft. In the high-speed aircraft area, IRO researchers are active participants in optimizing the aircraft configuration and structure in the HISAIR project at Langley. Near-term work involves integrating aerodynamics, structures, and performance in the design process. In the rotorcraft activity, emphasis will be on producing a fully-integrated aerodynamic-dynamic-structural optimization procedure for a helicopter rotor blade and initiating a comprehensive validation activity the rotorcraft optimization methods in which analytically-design blades will be fabricated and tested to assess optimality and behavior of the designs. In the controls-structure integration research, and optimization procedure developed in the past year for simultaneously optimizing a structure and control system will be extended to incorporate more comprehensive structural constraints including buckling and strength requirements.

## **CONCLUDING REMARKS**

This publication documents the F.Y. 1990 accomplishments, research and technology highlights, and F.Y. 1991 plans for the Structural Dynamics Division.

# LANGLEY RESEARCH CENTER

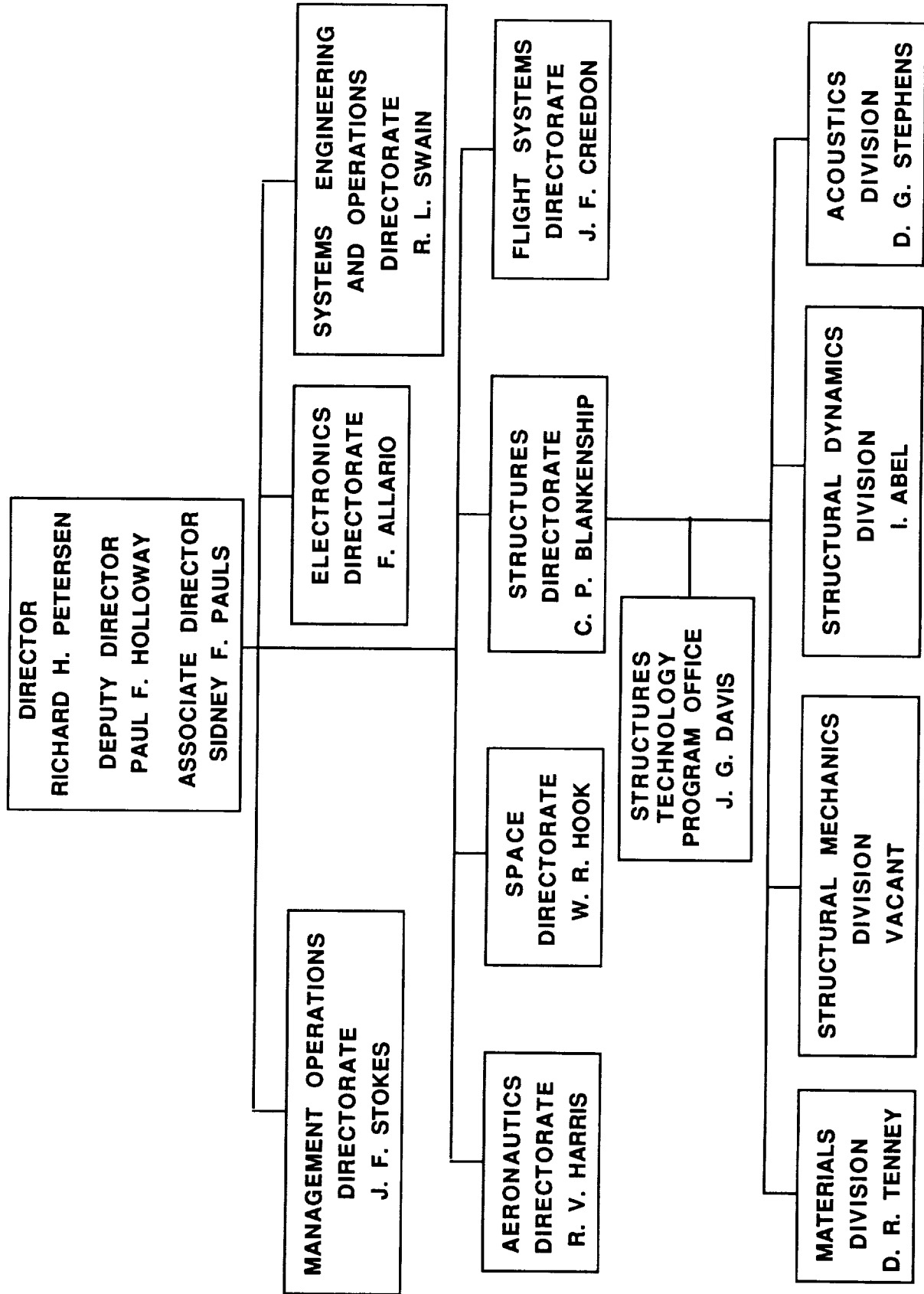


Figure 1.



STRUCTURAL DYNAMICS DIVISION  
 I. ABEL, CHIEF  
 R. DOGGETT, ASSISTANT CHIEF  
 804-864-2934

AEROSERVOELASTICITY  
 BRANCH  
 T. NOLL, HEAD  
 W. WHITLOW, ASST. HEAD  
 804-864-2821

ANALYSIS METHODS  
 DESIGN METHODS  
 APPLICATIONS  
 R/C STRUCTURAL DYN.

UNSTEADY  
 AERODYNAMICS  
 BRANCH  
 J. MALONE, HEAD  
 804-864-2257

THEORY DEVELOPMENT  
 APPLICATIONS  
 VALIDATION

CONFIGURATION  
 AEROELASTICITY BRANCH  
 R. RICKETTS, HEAD  
 C. ECKSTROM, ASST. HD  
 804-864-1207

A/C AEROELASTICITY  
 R/C AEROELASTICITY

SPACECRAFT DYNAMICS  
 BRANCH  
 B. HANKS, HEAD  
 M. GILBERT, ASST. HEAD  
 804-864-4324

CSI GROUND TEST METHODS  
 OPTIMAL SPACECRAFT  
 PERFORMANCE  
 MISSION DYNAMICS

INTERDISCIPLINARY  
 RESEARCH OFFICE  
 J. SOBIESKI, HEAD  
 H. ADELMAN, DEPUTY  
 804-864-2802

DESIGN METHODS  
 ALGORITHMS  
 APPLICATIONS

LANDING AND IMPACT  
 DYNAMICS BRANCH  
 J. TANNER, HEAD  
 H. CARDEN, ASST. HEAD  
 804-864-1301

TIRE MODELING  
 CRASH DYNAMICS

Figure 2.

# STRUCTURAL DYNAMICS DIVISION

## LONG RANGE THRUSTS

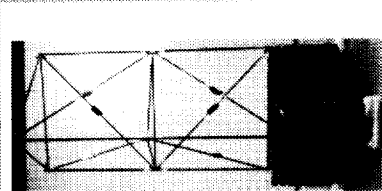
### AERONAUTICS

- TRANSPORT AIRCRAFT
    - \* AEROELASTICITY
    - \* LANDING AND IMPACT DYNAMICS
  - HIGH PERFORMANCE AIRCRAFT
    - \* AEROELASTICITY
  - ROTORCRAFT
    - \* AEROELASTICITY
  - ANALYTICAL METHODS
- SPACE
- LARGE SPACE STRUCTURES
    - \* STRUCTURAL DYNAMICS
    - \* CONTROLS-STRUCTURES INTERACTION

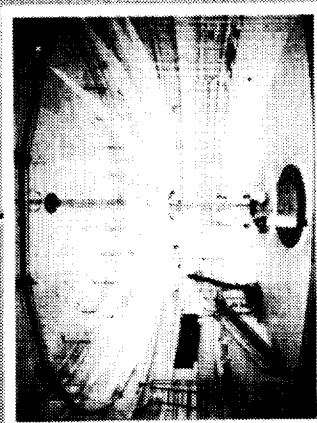
# STRUCTURAL DYNAMICS DIVISION

## SPACECRAFT DYNAMICS LABORATORY

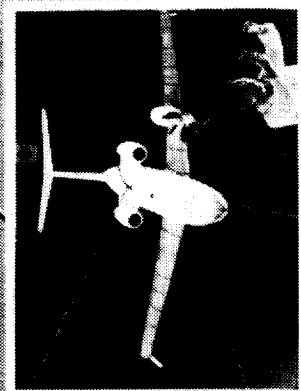
## TRANSONIC DYNAMICS TUNNEL



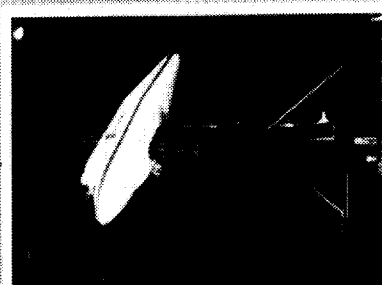
HIGH BAY AREAS



16M / THERMAL VACUUM CHAMBER



TDT

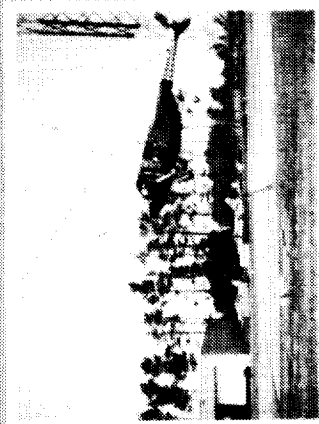
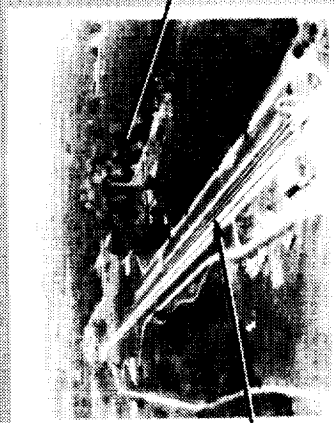


HOVER FACILITY

## LANDING AND IMPACT DYNAMICS FACILITY



AIRCRAFT LANDING DYNAMICS

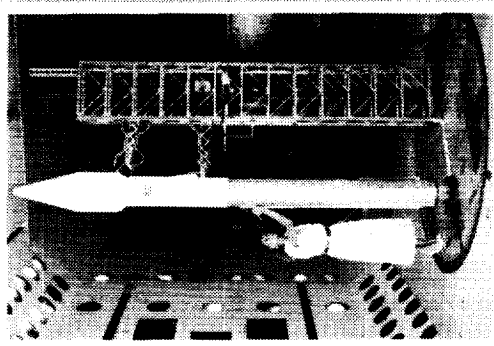


IMPACT DYNAMICS

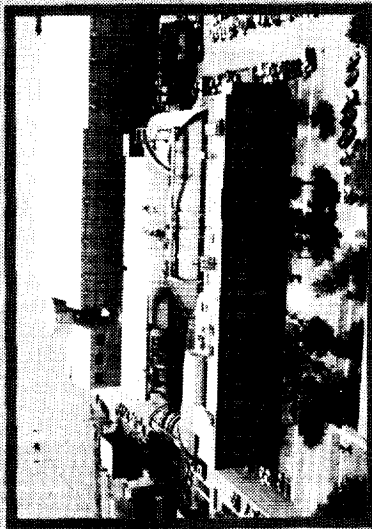
Figure 4.

# CONFIGURATION AEROELASTICITY

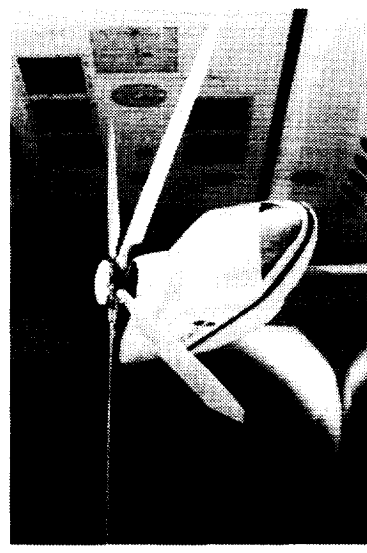
SPACECRAFT



TRANSONIC DYNAMICS TUNNEL



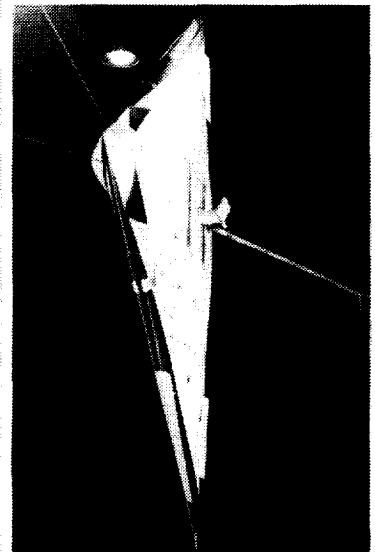
ROTORCRAFT



BENCHMARK MODEL



AIRCRAFT



HIGH-SPEED ROTORCRAFT

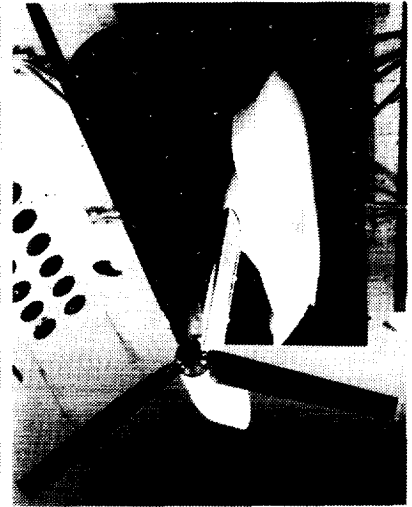


Figure 5.

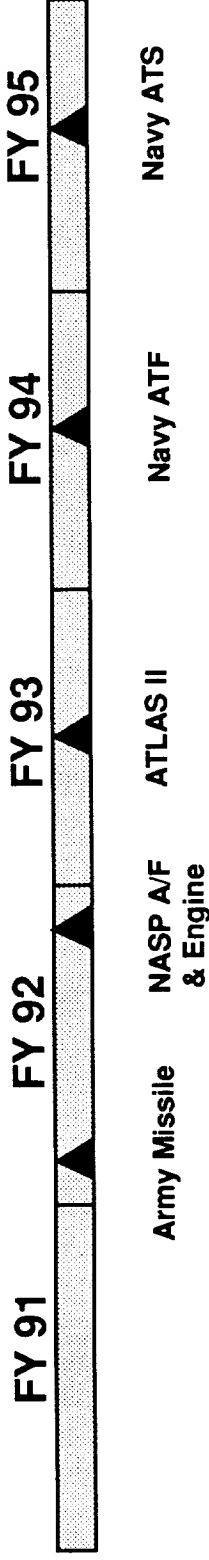
# CONFIGURATION AEROELASTICITY FUTURE PLANS (FY 91-95)

## GOAL

PREDICTION AND CONTROL OF AEROELASTIC RESPONSE

## KEY OBJECTIVES

- VERIFY THAT NEW NASA/DOD FLIGHT VEHICLES HAVE ADEQUATE AEROELASTIC PROPERTIES



## ● BENCHMARK MODELS



Figure 6 (a).

# CONFIGURATION AEROELASTICITY FUTURE PLANS (FY 91-95)

## GOAL

PREDICTION AND CONTROL OF AEROELASTIC RESPONSE

## KEY OBJECTIVES

- UNDERSTAND AEROELASTIC CHARACTERISTICS OF ADVANCED FLIGHT VEHICLES

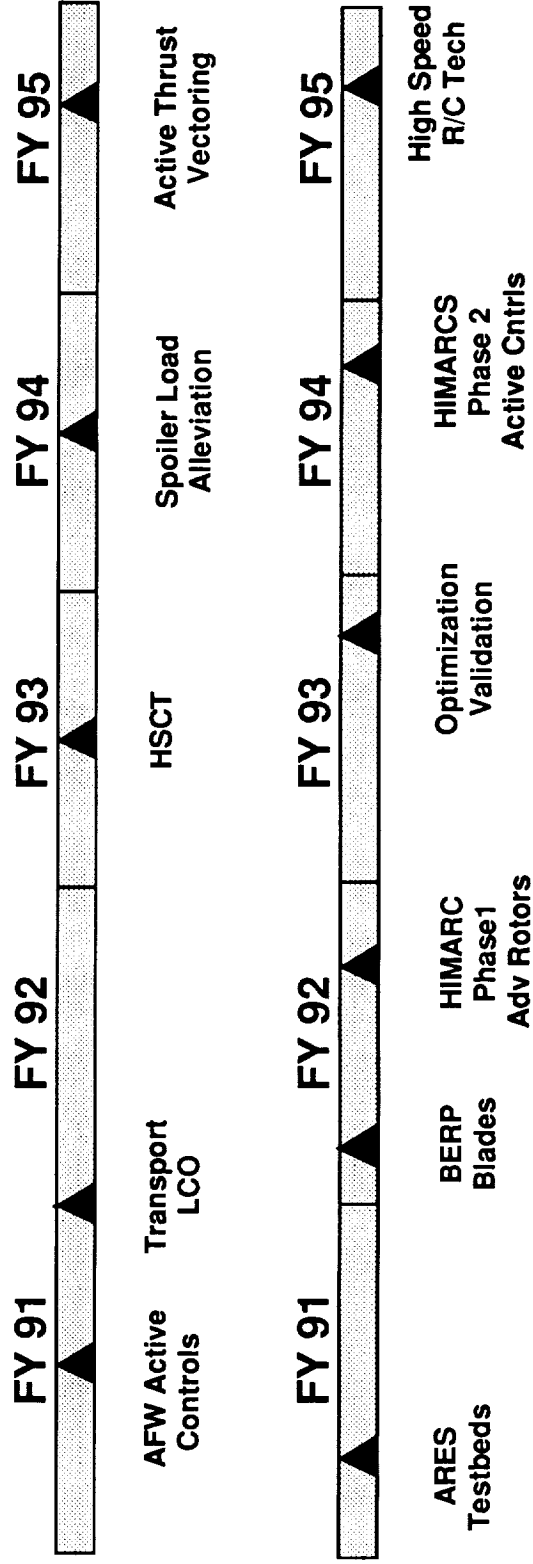


Figure 6 (b).

# CONFIGURATION AEROELASTICITY FUTURE PLANS (FY 91-95)

## GOAL

PREDICTION AND CONTROL OF AEROELASTIC RESPONSE

## KEY OBJECTIVES

- MAINTAIN TDT AS A UNIQUE NATIONAL FACILITY

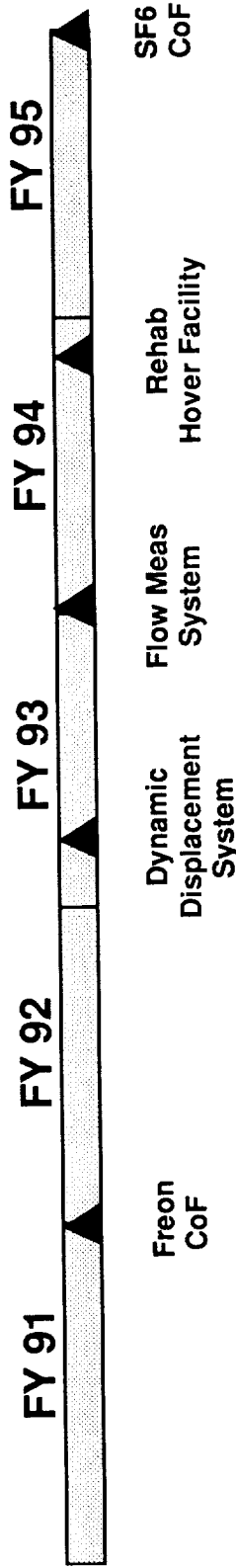


Figure 6 (c).

# STATICALLY UNSTABLE MODEL FLOWN SUCCESSFULLY USING ONBOARD STABILITY AUGMENTATION SYSTEM IN TDT

Michael H. Durham and Donald F. Keller  
Configuration Aeroelasticity Branch

RTOP 505-63-50

**Research Objective:** Fighter aircraft are being designed to fly statically unstable to improve performance and combat maneuverability. As a result, it is becoming more difficult to test full-span models mounted on cable systems which accurately scale aeroelastic characteristics. A study was conducted in the Transonic Dynamics Tunnel (TDT) to develop and demonstrate the ability to test a statically unstable aeroelastic flying model using an onboard stability augmentation system (SAS).

**Approach:** A full-span aeroelastic flying-model was designed and constructed to represent an advanced fighter aircraft. Statically stable and unstable test conditions were achieved with a movable mass system within the model that allowed the center of gravity to vary over a wide range (12%) of mean aerodynamic chord. An onboard hydraulic system was used to actuate horizontal tail surfaces providing pitch and roll stability. Rate gyros were mounted in the model to provide pitch and roll inputs to the stability augmentation system. Analog control systems were designed to command the individual horizontal tail surfaces using pilot trim inputs, the horizontal tail position, and gyro feedbacks. A secondary control system was used to evaluate control law changes with open loop transfer functions while the primary system was used to stabilize the flying model. Model tests were conducted in the TDT over a Mach number range of 0.6 to 1.2 using both a heavy gas (R-12) and air as test mediums. The attached photograph shows the model onboard hydraulic system, the movable mass mechanism, and the pitch and roll rate gyros.

**Accomplishment Description:** The model was first flown on the two-cable mount system with the movable mass forward. Flying characteristics were then evaluated both with and without the SAS engaged. Without the active SAS the model was marginally stable and the handling qualities became unacceptable above Mach 1.0. The SAS improved the flight handling characteristics, allowing the model to be flown up to a Mach number of 1.1 and a dynamic pressure of 300 psf. The shaded regions in figure 7(b) represent the increased test envelopes achieved with the use of the SAS. The dashed lines indicate the test limits without the SAS. With the movable mass in the most rearward position, open loop measurements determined the model would have been statically unstable at dynamic pressures above 100 psf. The active SAS allowed testing up to dynamic pressures of 250 psf.

**Significance:** The capability to fly statically unstable aeroelastic models was demonstrated in the TDT. These tests evaluated the use of an active SAS to allow flutter testing of a model that accurately scaled a statically unstable aircraft. The active control system provided the required 150% increase in model test dynamic pressure to allow tunnel tests of flutter critical aircraft store configurations. This system also provided improved model flight handling characteristics for marginally stable configurations.

**Future Plans:** Further tests are planned to determine the effects of the stability augmentation system on model flutter characteristics.

Figure 7 (a).



# STATICALLY UNSTABLE MODEL FLOWN SUCCESSFULLY USING ONBOARD STABILITY AUGMENTATION SYSTEM IN TDT

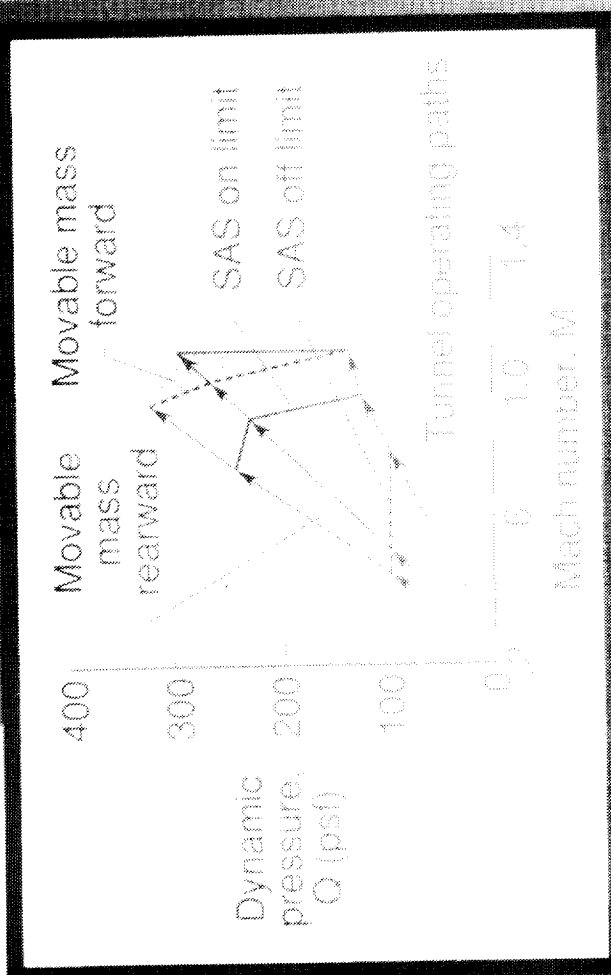
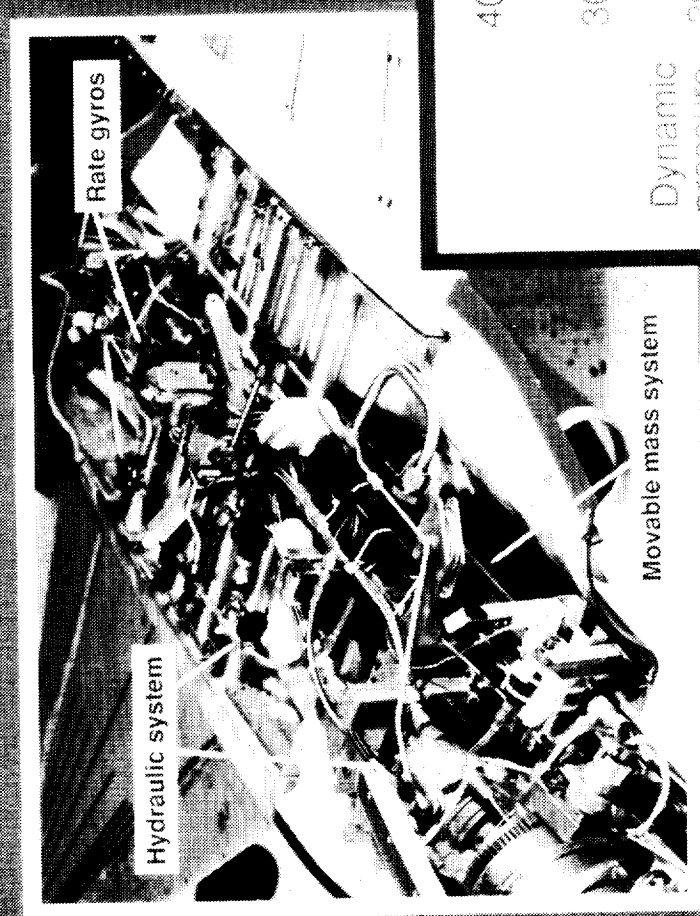


Figure 7 (b).

## AILERON BUZZ CHARACTERISTICS ARE DETERMINED FOR SEVERAL NASP WING CONFIGURATIONS

Ellen C. Parker, Charles V. Spain, and David L. Soistmann  
Lockheed Engineering and Sciences Company

RTOP 505-63-50

**Research Objective:** Aileron buzz is a term used to describe potentially violent, single-degree-of-freedom aileron oscillations which occur primarily at transonic speeds. Earlier research suggests that this phenomenon may be related to the formation of shock waves on the wing surface. The objective of this study was to determine if aileron buzz would occur on generic National Aerospace Plane (NASP) wing configurations, and to observe how variations in geometry would affect the occurrence or behavior of buzz. This research was conducted in support of the NASP Technology Maturation Program. The delta-wing geometries are representative of NASP design concepts.

**Approach:** Four composite aileron buzz models with full-span ailerons and of various delta-wing geometries were designed and built for testing in the TDT. A photo of one of these models mounted with a splitter plate is provided in the top of figure 8(b). A sketch showing model dimensions is in the lower left of this figure. The four models consisted of two planform variations and two airfoil thicknesses for each planform. All of the models were first tested for conventional flutter at atmospheric tunnel stagnation pressure at subsonic Mach numbers with dynamic pressures up to 200 psf. Several additional tests were then made at various sub-atmospheric stagnation pressures to determine aileron buzz boundaries in the transonic range.

**Accomplishment Description:** Single-degree-of-freedom aileron oscillations, both limit-amplitude and divergent, were observed at transonic speeds for each model. The Mach number and dynamic pressures at which divergent oscillations occurred are indicated in the lower right plot. Flutter produced by the coupling of the aileron pitch mode and the wing first bending mode occurred at Mach numbers below buzz onset for one configuration only. The Mach number and dynamic pressures at which flutter occurred is also in the lower right plot. Increasing the wing leading-edge sweep appeared to increase the Mach number at which divergent aileron oscillations occurred. Increasing the airfoil thickness had a similar effect. At lower dynamic pressures the onset of buzz occurred gradually with limited-amplitude oscillations observed prior to divergence. At higher dynamic pressures the onset of buzz was more explosive and less predictable. In one instance, the aileron was lost.

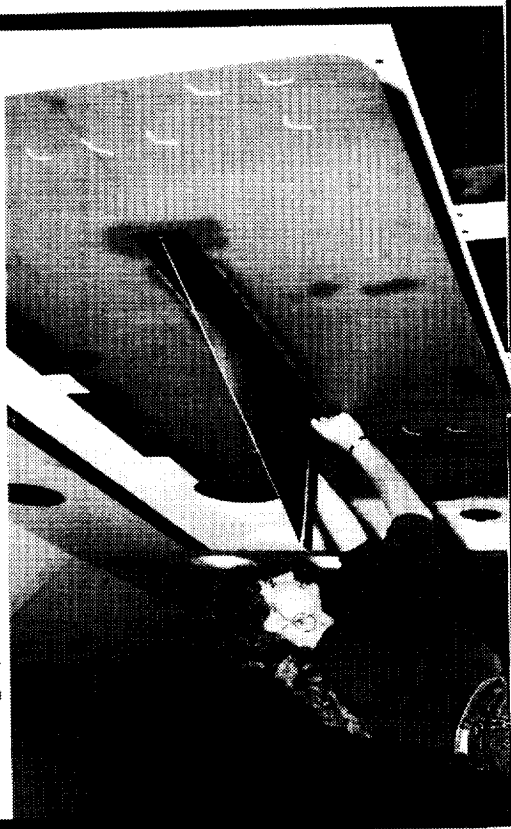
**Significance:** Although the implementation of irreversible, hydraulically controlled actuating systems has greatly reduced the problem of control surface buzz on most modern aircraft, the NASP is weight critical and does not have the luxury of a very conservatively designed actuating system. This study provides some experience in estimating the potential for buzz and its effects on the actual NASP flight vehicle.

**Future Plans:** The current NASP Government Work Package on Vehicle Flutter Evaluation includes plans for transonic flutter models. If the NASP vehicle design is to include similar full-span control surfaces, aileron buzz evaluation will be inherent in these future studies.

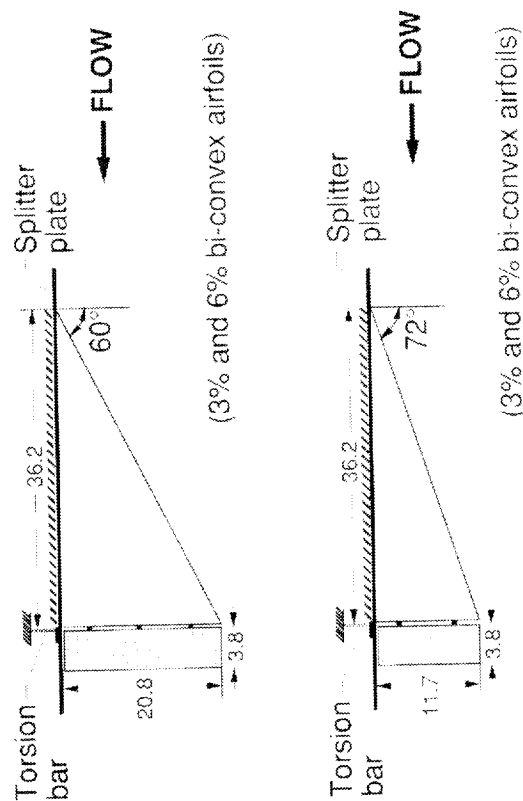
Figure 8 (a).

# AILERON BUZZ CHARACTERISTICS ARE DETERMINED FOR SEVERAL NASP WING CONFIGURATIONS

## COMPOSITE BUZZ MODEL



## MODEL DIMENSIONS



## BUZZ BOUNDARIES

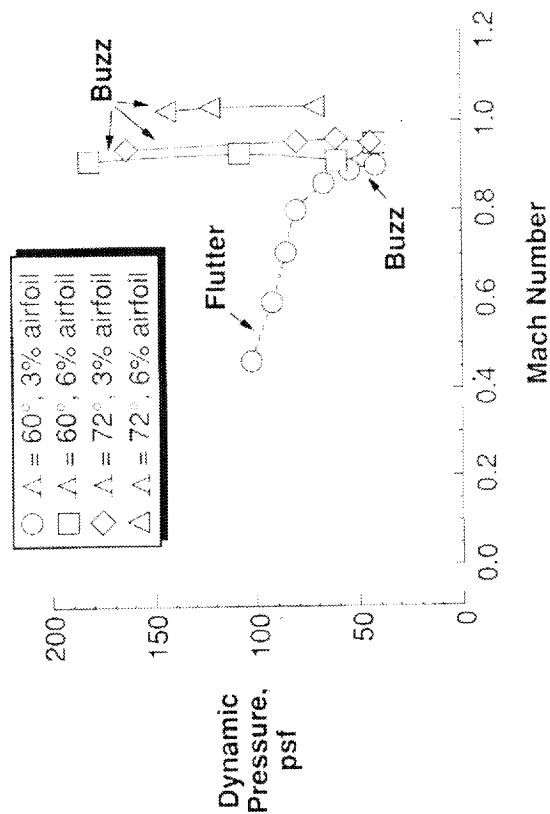


Figure 8 (b).

## NAVY ADVANCED FIGHTER SHOWN FREE FROM FLUTTER IN TDT TESTS

Moses G. Farmer and Maynard C. Sandford  
Configuration Aeroelasticity Branch

RTOP 505-63-50

**Research Objective:** Modern fighter aircraft must be designed so that their performance capabilities are not degraded by flutter restrictions. The objective of this program is to verify that the Navy Advanced Fighter (A-12) aircraft will have the required flutter margin of safety throughout its flight envelope. The flight envelope is defined by Mach number and altitude limits to which the aircraft can fly.

**Approach :** A dynamically scaled aeroelastic model of the A-12 was tested in the Langley Transonic Dynamics Tunnel (TDT) as part of the flutter clearance program figure 9(b) shows the model installed in the TDT on a cable mount system that has been used previously for many other models. The cable mount system is flexible enough to adequately simulate the vibrations of the aircraft in flight. Initial testing was conducted using an overly stiff (dummy) model to determine dynamic stability of the model on the cable system. In addition, some configurations that were considered most likely to flutter were first tested on a sting mount to increase safety of the model. All tests were conducted using Freon in the TDT. Because of the environmental concerns regarding Freon use, two significant changes to the tests were made to reduce the amount of Freon lost. First, the model test plans were limited to the minimum number of model configurations required to enable safe flight flutter tests of the full-scale vehicle. Furthermore, the testing methods were revised to reduce the amount of gas processing.

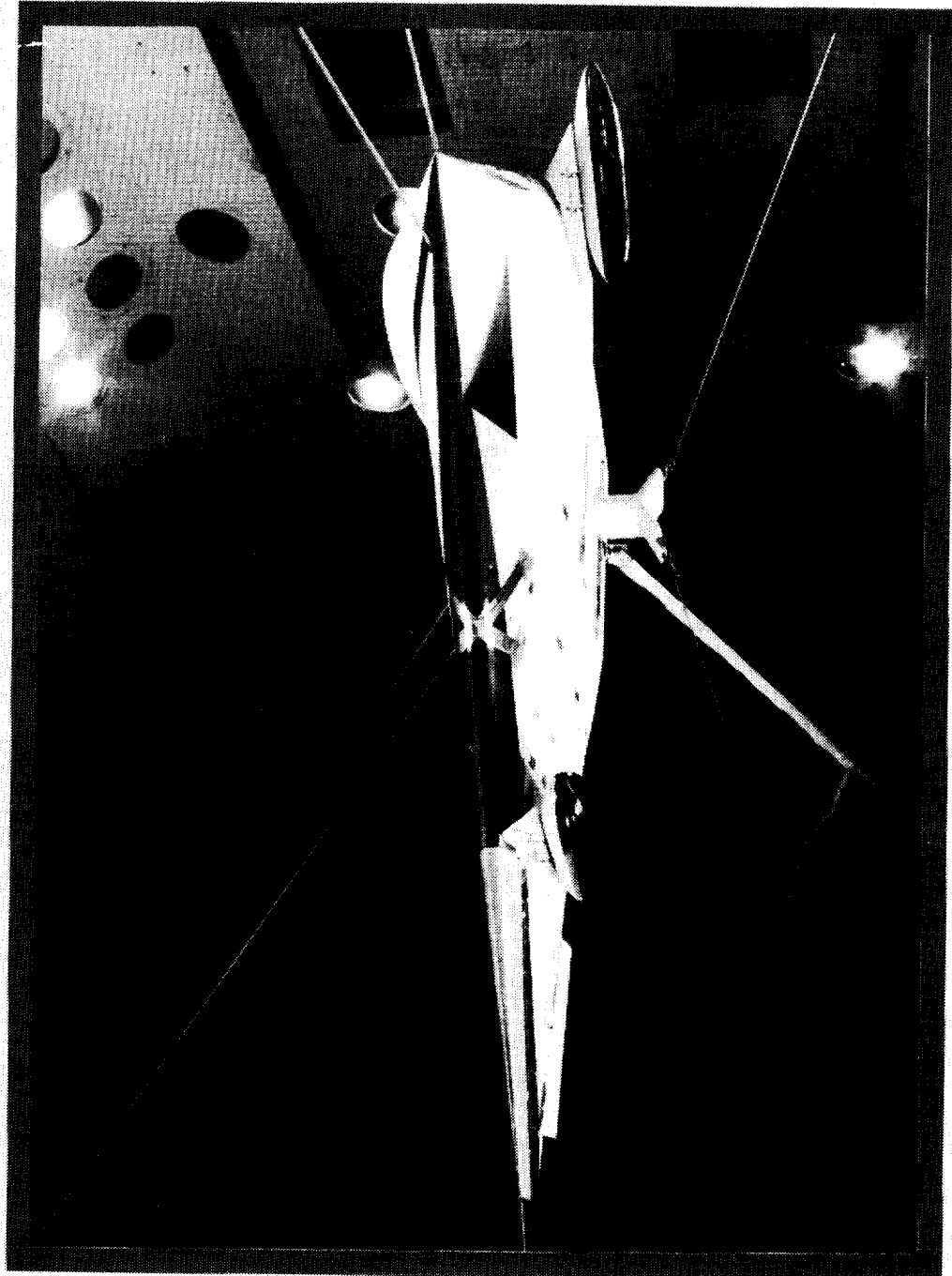
**Accomplishment Description:** A total of 41 configurations were tested during four wind tunnel entries in the TDT between July 1989 and August 1990. Model configurations that were tested during this time include the clean wing and the wing configured with internal and external stores. Some configurations were tested to determine the influence on flutter of free-play effects and flexibility in the wing fold joints and wing control surfaces. Furthermore, fuel-mass effects on flutter was also determined. All configurations that were tested were shown to have the required flutter margins of safety throughout the vehicle flight envelope. Finally, using the modified test plan and testing methods enabled an approximate 50 percent reduction in the amount of Freon that was lost.

**Significance:** Because these tests indicate that the aircraft has no flutter problems, the development of the A-12 can proceed with greater confidence. Also, the aircraft flight testing required for flutter clearance will be significantly reduced.

**Future Plans:** A fifth wind tunnel test has been scheduled for 1992 in the event that it is required. This test will be needed only if future ground vibration tests of the full-scale vehicle show significant unresolvable differences in structural dynamic characteristics when compared with those of the model that has been tested in the TDT. This requirement to test will be determined by NASA, the Navy and the contractors sometime during 1991.

Figure 9 (a).

**NAVY ADVANCED FIGHTER SHOWN FREE  
FROM FLUTTER IN TDT TESTS**



**Figure 9 (b).**

# EFFECTS OF THERMAL GRADIENTS ON STRUCTURAL VIBRATION FREQUENCIES INVESTIGATED

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RTOP 505-63-50

**Objective:** The National Aero-Space Plane (NASP) will be subjected to aerodynamic heating which is likely to cause steep thermal gradients on the vehicle structure. Historically, very little research has been done to predict the aeroelastic effects of such large thermal gradients. The objective of this work was to evaluate aerothermoelastic analytical procedures that were recently developed under the NASP Technology Maturation Program.

**Approach:** Engineers at Ames-Dryden Flight Research Facility conducted thermoelastic experiments in support of NASP which included vibration testing of a free hanging rectangular aluminum plate subjected to nonuniform heating. While these data were successfully used for test/analysis correlation for a solid plate, additional correlation studies for a more representative box structure was desired. An aluminum wing-box model (see photo in fig. 10(b)) with spars, ribs and curved skin panels was designed and tested at NASA Langley. Shown in the lower left of the figure are the measured temperature contours at the hottest test condition resulting from intense heating of the model leading edge. Thermocouple and accelerometer data were recorded simultaneously during the heating/cooling cycle. The temperature data were incorporated into the thermoelastic analysis procedures, which consist of routines developed for use with a finite element modeling program (Engineering Analysis Language). The procedures automatically account for the changes in material properties at elevated temperatures, and the effects of internal stresses on stiffness resulting from nonuniform thermal expansion.

**Accomplishment Description:** The results shown on the right of the figure indicate that while the trends predicted analytically are correct, the magnitudes of the predicted frequency changes are often less than those measured. Wing-box modal frequencies sometimes increased with nonuniform heating, whereas previous research (including experiments at Ames-Dryden) indicates that solid plate frequencies consistently decrease with nonuniform heating.

**Significance:** This experimental investigation provides confidence that recently developed finite-element procedures can provide reasonable predictions of aerothermoelastic characteristics of aircraft type structures subjected to nonuniform heating. This research is important for aeroelastic analysis of hypersonic vehicles.

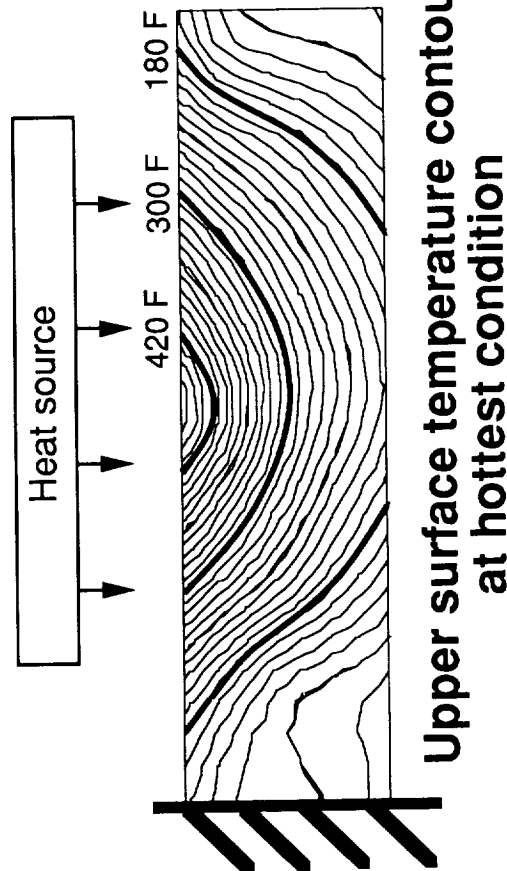
**Future Plans:** This work will continue in support of NASP Government Work Packages on aeroelasticity.

Figure 10 (a).

# EFFECTS OF THERMAL GRADIENTS ON STRUCTURAL VIBRATION FREQUENCIES INVESTIGATED



Test arrangement



Frequency change due to thermal gradient

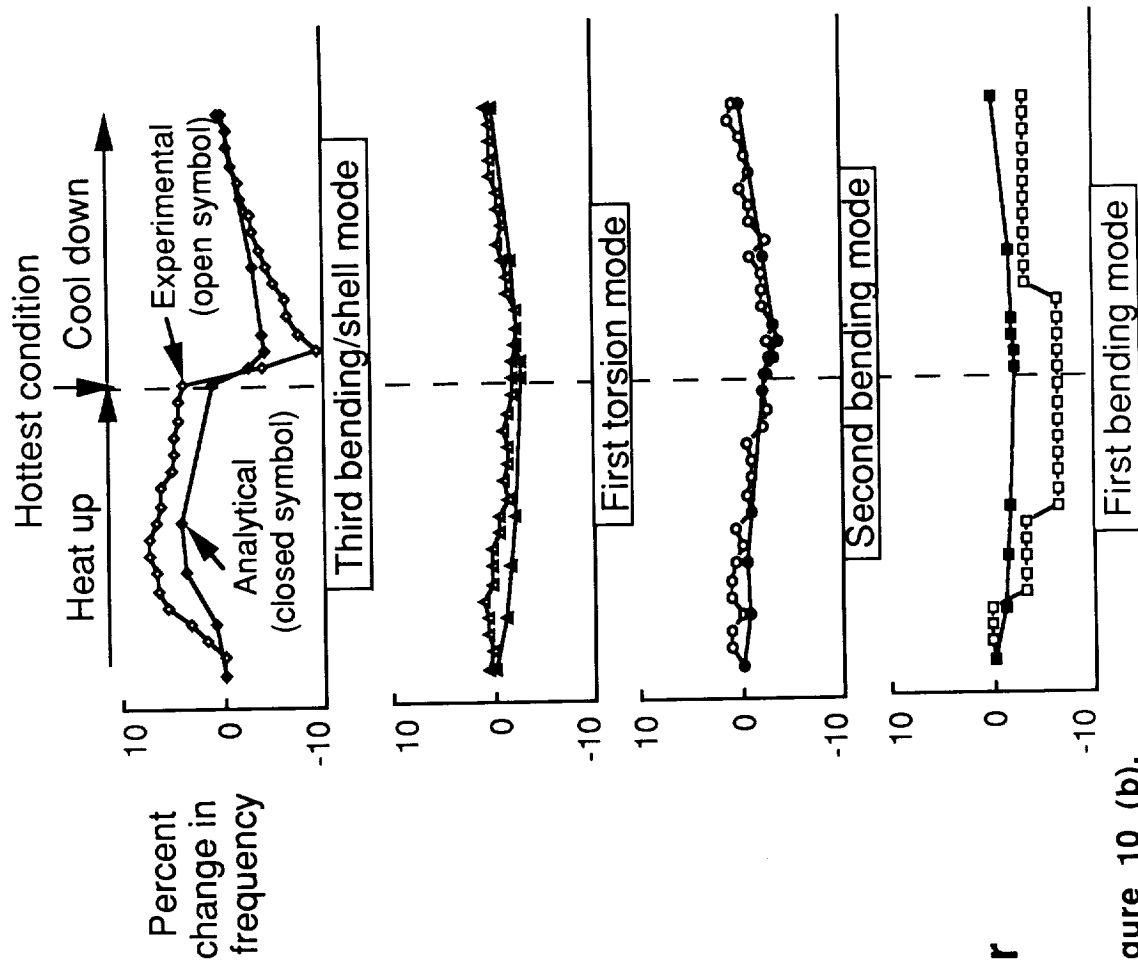


Figure 10 (b).

## FLUTTER CHARACTERISTICS DEFINED FOR TRAIL ROTOR MODEL IN TDT

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Configuration Aeroelasticity Branch

RTOP 505-63-50

**Research Objective:** The Trail Rotor vehicle is a conceptual design for a future high-speed rotorcraft. This tilt-rotor vehicle includes a fixed wing with a gear-box nacelle and rotor blades on each wing tip. In the take-off, landing, and hover modes of operation, the gear-box nacelles are in the vertical position with the blades deployed horizontally. During conversion to the forward flight mode, the nacelles tilt aft and the blades are feathered and then folded back into a fixed trailing position. A Trail Rotor vehicle will be powered in both hover and forward flight by turbo-fan engines located near the wing root. The objective of this study was to investigate the flutter behavior of a simple Trail Rotor model in the forward flight mode.

**Approach:** Four different components of this Trail Rotor model were tested for flutter in the TDT. The clean wing was cantilever mounted on the tunnel sidewall. The wing was constructed of an aluminum flat plate with a NACA 65A010 foam airfoil bonded to it. The first configuration tested was the clean wing only. The second configuration tested included the clean wing plus a tip pod representing the gear-box nacelle. The third configuration tested included the clean wing and the tip pod plus four rigid trailing rotor blades. A photo of this complete configuration is shown in figure 11(b). The fourth configuration tested was the same as the third configuration except that the rotor blades were replaced with a thin vertical steel bar to represent the mass and inertia of the blades but not the aerodynamics.

**Accomplishment Description:** Flutter tests were conducted on a simple Trail Rotor model in the TDT up to  $M=0.90$ . The design Mach number for a Trail Rotor vehicle is expected to be 0.75. No flutter points were obtained for the clean wing configuration within the TDT air operating envelope. This included high points at a dynamic pressure of 300 psf at a Mach number of 0.48 and at a dynamic pressure of 258 psf at a Mach number of 0.88. The wing/pod configuration flutter boundary is shown with the circular symbols in the plot. This configuration showed a steep drop in flutter boundary above  $M=0.80$ . At lower Mach numbers, the tunnel's operating envelope in air did not allow any flutter points to be obtained at less than Mach 0.75. The wing/pod/blades configuration flutter boundary is shown with the square symbols in the plot. This flutter boundary is lower in dynamic pressure and is not as steep as the wing/pod configuration boundary. With the exception of the flutter point obtained at Mach 0.46, this boundary tends to be rather flat subsonically. The wing/pod/inertia-mass bar configuration flutter boundary is shown in the plot with the triangular symbols. This boundary is slightly lower in dynamic pressure than the wing/pod/blades configuration but shows the same general trend. The higher flutter boundary for the wing/pod/blades configuration most likely results from the aerodynamic damping derived from the blades.

**Significance:** This early study showed some basic flutter characteristics for a conceptual Trail Rotor vehicle in the forward flight mode which can be used by designers. The aerodynamic damping of the blades was shown to be beneficial from a flutter standpoint.

**Future Plans:** Some preliminary analysis has shown good correlation with the experimental data. Upon completion, analytical comparisons with the experimental data will be reported.

Figure 11 (a).



# FLUTTER CHARACTERISTICS DEFINED FOR TRAIL ROTOR MODEL IN TDT

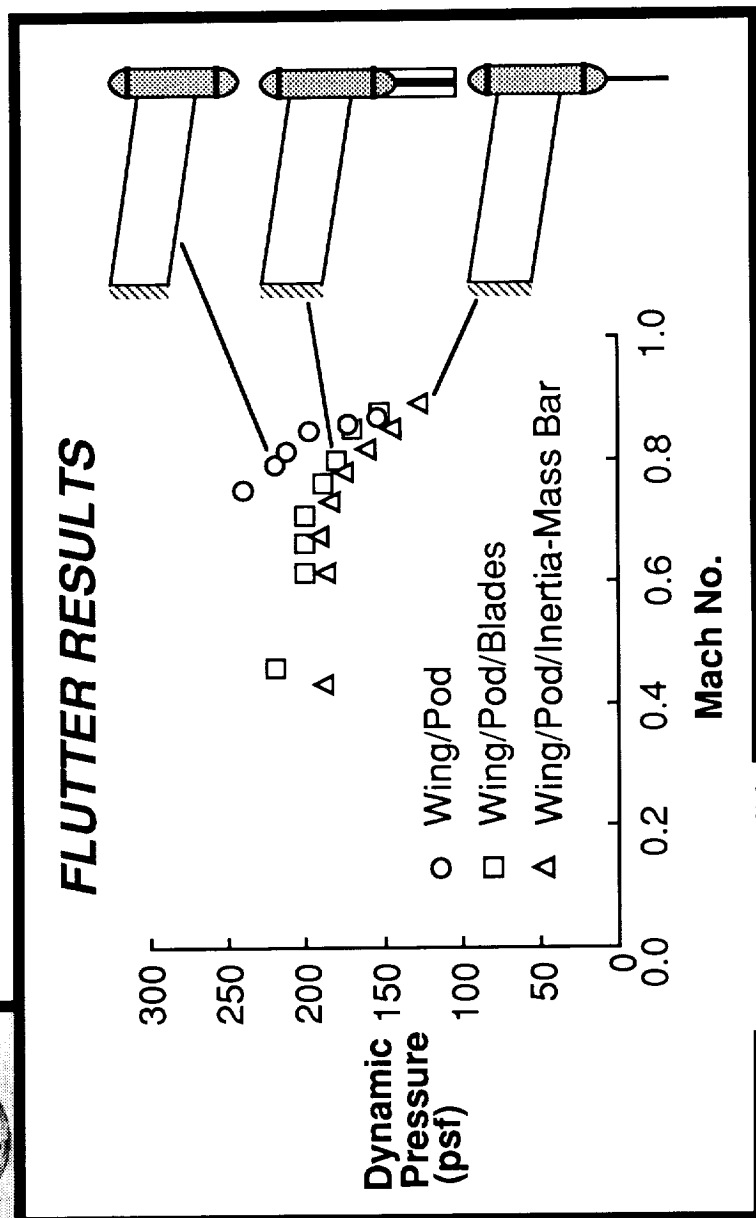


Figure 11 (b).

## FIRST BENCHMARK-MODEL-PROGRAM TEST SUCCESSFULLY COMPLETED

Jose A. Rivera, Bryan E. Dansberry, Moses G. Farmer and Clinton V. Eckstrom  
Configuration Aeroelasticity Branch

Robert M. Bennett and David A. Seidel  
Unsteady Aerodynamics Branch

RTOP 505-63-50

**Research Objective:** A Benchmark Models Program has been initiated at Langley with a primary objective of obtaining data for CFD code development, evaluation and validation. The first model in the series, a wing with a conventional airfoil supported on a flexible mount system, was tested to define the conventional flutter boundary, the angle-of-attack flutter boundary and other transonic instability boundaries with simultaneous measurement of surface pressures during flutter.

**Approach:** A rigid rectangular wing of panel aspect ratio 2.0 with a NACA 0012 airfoil was tested in the Transonic Dynamics Tunnel (TDT) on the flexible Pitch and Plunge Apparatus. A photo of the model is shown in figure 12(b). The model was equipped with insitu pressure transducers to measure wing upper and lower surface steady and unsteady pressures along a chordline at the 60-percent span station. The model and support system were also instrumented with accelerometers and strain gage bridges for measurement of model frequencies, displacements and forces. A ground vibration test was performed to define the wind-off structural dynamic characteristics of the model system. Wind-on data were obtained in the Mach number range from 0.3 through 0.97.

**Accomplishment Description:** The first wind tunnel test has been completed. The Mach number effects on the conventional flutter boundary (coupling of pitch and plunge modes) for the model at zero-degrees alpha (angle-of-attack) are shown as a function of dynamic pressure and Mach number in the data plot at the lower left of figure 12(b). A narrow instability region is also shown near Mach number 0.90 in which the mode of oscillations was primarily plunge motion. Angle-of-attack effects on model flutter at Mach number 0.78 are shown in the plot at the lower right portion of the figure. At angles of attack greater than about  $4.3^\circ$  the motion was primarily in the pitch mode and is considered to be shock induced stall flutter. At other Mach numbers (not shown) the transition to stall flutter occurred at somewhat different angles of attack. Instrumentation time history records were recorded at most instability points as well as at some subcritical test conditions. Flow studies were also performed using both tufts and liquid crystals to define shock locations and lines of separation.

**Significance:** The availability of an extensive data set defining model structural dynamic characteristics and measured model instability boundaries (flutter, etc.) along with associated steady and unsteady pressure measurements is expected to be a useful tool for the development, evaluation, and validation of CFD methods.

**Status/Plans:** Data reduction is ongoing. Final results will be documented in a series of formal publications. The model is being instrumented with an additional set of insitu pressure transducers for measurement of unsteady surface pressures at the 95% span station as well as at the 60% station where measurements are currently available. The next test is scheduled for January 1991.

Figure 12 (a).

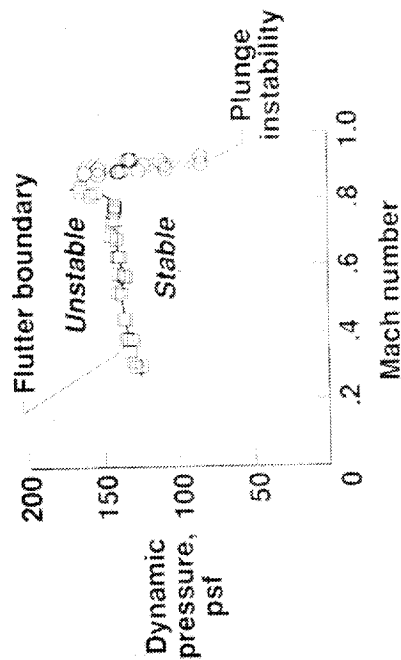
# FIRST BENCHMARK-MODEL-PROGRAM TEST SUCCESSFULLY COMPLETED IN TDT

NACA 0012 MODEL



## MACH NUMBER EFFECTS

$\alpha = 0^\circ$



## ANGLE-OF-ATTACK EFFECTS

$M = 0.78$

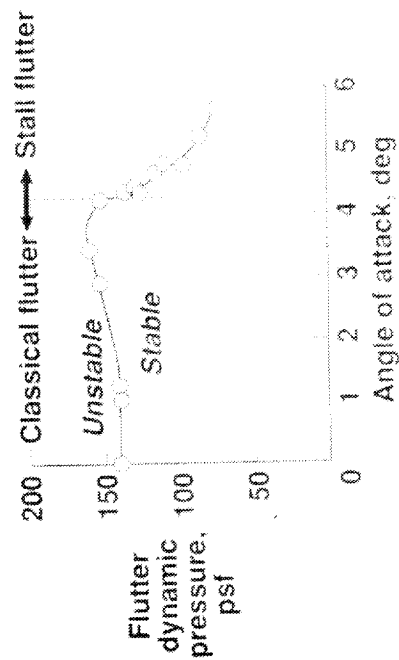


Figure 12 (b).

## TDT TESTS ENHANCE KNOWLEDGE OF HELICOPTER ROTOR NODALIZATION METHOD

William T. Yeager, Jr.

M-Nabil Hamouda, Lockheed Engineering & Sciences Company  
Configuration Aeroelasticity Branch

RTOP 505-63-36

**Research Objective:** A major concern of helicopter manufacturers and operators is the reduction of fuselage vibration levels. These vibrations can cause problems such as crew and passenger discomfort, structural fatigue, and damage to sensitive electronic equipment. A primary cause of fuselage vibration is the interaction between the rotor structure and the aerodynamic forces and moments imposed on the rotor blade. This interaction produces vibratory forces at the root of the blade which are then transmitted through the hub into the fuselage. One means of reducing fuselage vibration is by attenuating the vibratory forces transmitted to the fuselage. A research effort in the Langley Transonic Dynamics Tunnel (TDT) involved the evaluation of a vibration attenuation method known as rotor nodalization. Nodalization is a Bell Helicopter Textron design process usually applied to bearingless rotors. According to Bell analyses, tailoring mass and stiffness distributions for both the hub and blades to tune selected rotor modes may result in lower fixed-system vibration. For the TDT tests only designs incorporating variations in blade mass and stiffness were used.

**Approach:** A test was conducted in the TDT using baseline and nodalized rotor blades mounted on a bearingless hub. The blades and hub were built by Bell and provided under contract to Langley. All blades were tested on the Aeroelastic Rotor Experimental System (ARES) testbed. Each blade set was tested at the same nominal rotor lift, propulsive force, and rotor rpm over a range of forward speeds from transition (20-30 knots) to cruise (130 knots). At each test condition, measurements were made of the vibratory content of the ARES strain-gage balance forces and moments. These fixed-system measurements were used to evaluate differences between the baseline and nodalized rotors.

**Accomplishment Description:** Figure 13(b) shows typical results from the TDT test as well as representative normalized values of the baseline and nodalized blade property distributions. The data show that for the nodalized rotor the 4-per-rev fixed-system vertical force is higher compared to that of the baseline rotor for all forward velocities tested. These data are contrary to Bell analytical predictions. To determine if ARES tested dynamic non-linearities could have contaminated the strain-gage balance data, a comprehensive dynamic calibration of the testbed was conducted. Application of the dynamic calibration matrix to the data was found to substantiate the initial trends obtained.

**Significance:** The test of a nodalized rotor in the TDT served to show that changes to both blade mass and stiffness will alter fixed-system vibratory loads. These tests have also showed the importance of considering fixed-system dynamics in the design of a nodalized rotor. As a result of the TDT tests, Bell is in the process of reviewing the vibration indices used for the design process, as well as looking into the effect of rotor in-plane modes on rotor nodalization.

**Future Plans:** Future plans call for documentation of these results in a NASA formal publication. A rotating balance may be incorporated directly below the rotor hub on the ARES to augment future vibratory loads measurements.

Figure 13 (a).

# TDT TESTS ENHANCE KNOWLEDGE OF HELICOPTER ROTOR NODALIZATION METHOD

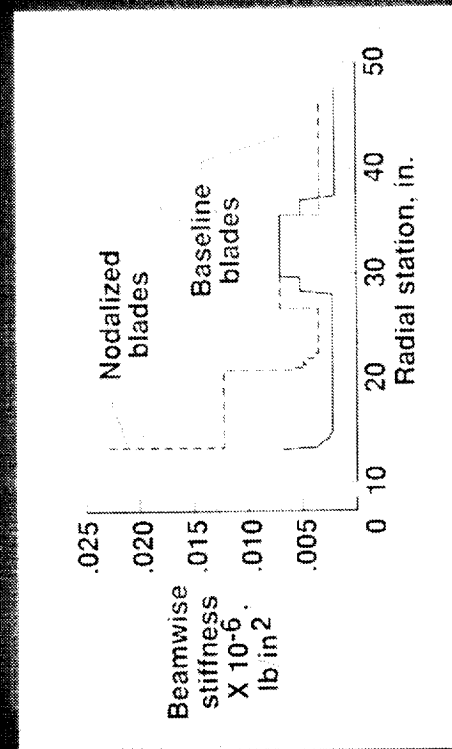
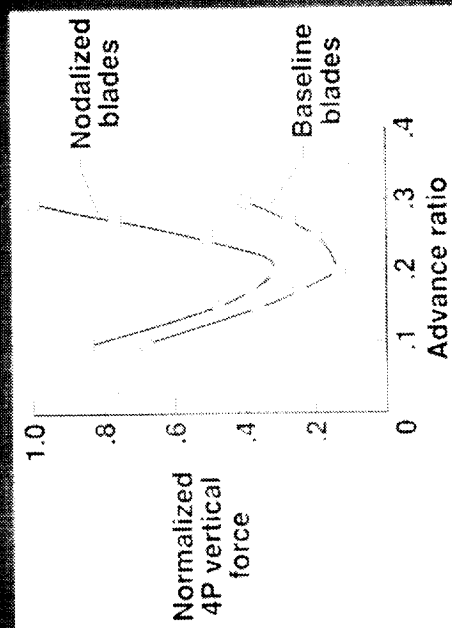
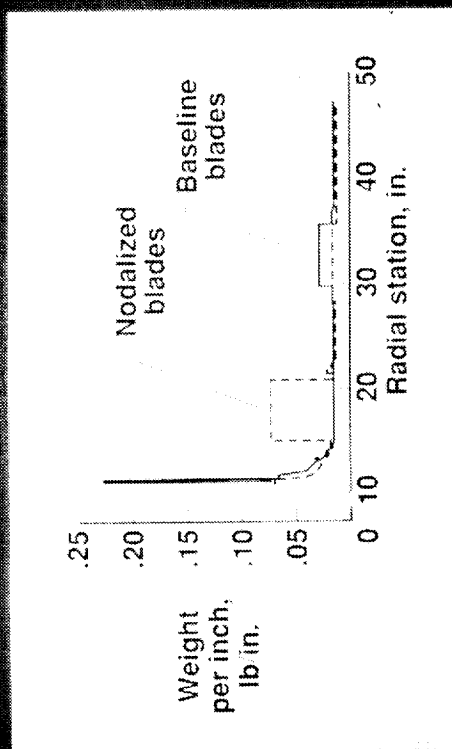
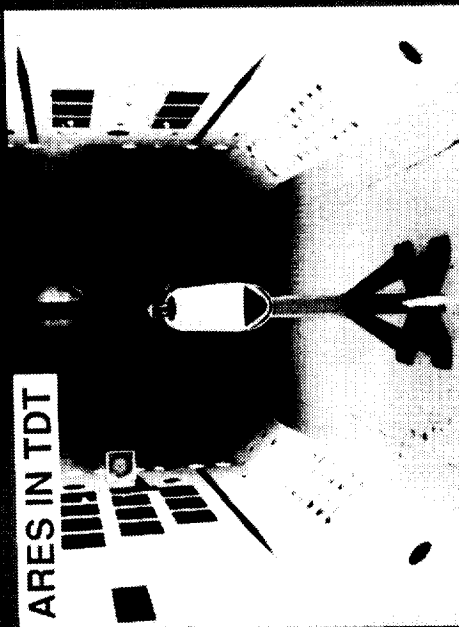


Figure 13 (b).

# AEROMECHANICAL STABILITY DATA BASE FOR PARAMETRIC HINGELESS ROTOR EXPANDED

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Lockheed Engineering & Sciences Company

Jeffrey D. Singleton and William T. Yeager, Jr.  
Configuration Aeroelasticity Branch

RTOP 505-63-36

**Research Objective:** One goal of the Aeroelastic Research Experimental System (ARES) effort in the Langley Transonic Dynamics Tunnel (TDT) is to develop the capability to successfully test hingeless and bearingless rotor configurations. An important part of this capability is the development of an experimental technique for accurate measurement of the aeromechanical stability of the coupled rotor-body system. In order to investigate the aeromechanical instability phenomenon, a research effort was started in the TDT several years ago. The objectives of the research are to generate a data base for analytical correlation and to ensure safe testing of hingeless and bearingless rotors in the TDT.

**Approach:** The initial phase of the research program involved two wind tunnel tests of the ARES first generation hingeless rotor (AHRO). The current test utilized the ARES second generation hingeless rotor (AHRO-II) which has improved fatigue life characteristics and a higher lead-lag frequency than the original AHRO. Initial run-up of the AHRO-II mounted on the ARES model was conducted in the Helicopter Hover Facility (HHF). Testing in hover and forward flight was performed in the TDT. The moving-block technique was utilized to measure rotor in-plane damping for determination of aeromechanical stability. Damping measurements were made for a range of parameters including rotor speed, collective pitch and blade droop. Initial attempts were made to measure damping in an autorotative condition.

**Accomplishment Description:** Testing in hover was conducted at different values of collective pitch over a range of rotor speeds. Testing in forward flight was performed over a range of advance ratios up to 0.35. Some illustrative results of in-plane damping values for both hover and forward flight are shown in figure 14(b). The data obtained show a trend of increasing damping with collective pitch. The figure also shows that in-plane damping decreases with increasing rotor speed. An unstable region is indicated in hover and forward flight. Similar results were obtained for configurations incorporating changes to blade droop.

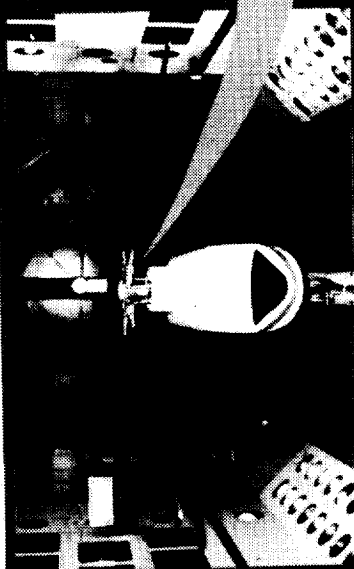
**Significance:** This test has expanded the aeromechanical stability data base for the parametric hingeless rotor. Consistent and repeatable measurements of the rotor in-plane damping were obtained. The experimental data will be used for future correlation with analytical codes. The test has continued to show that safe testing can be accomplished even near and into the instability region.

**Future Plans** Tests will be conducted with AHRO-II mounted on a modified ARES which has a static gimbal to allow for variation in roll and pitch frequencies. Future plans also call for correlating the experimental data with analytical methods and publishing the results in a formal report.

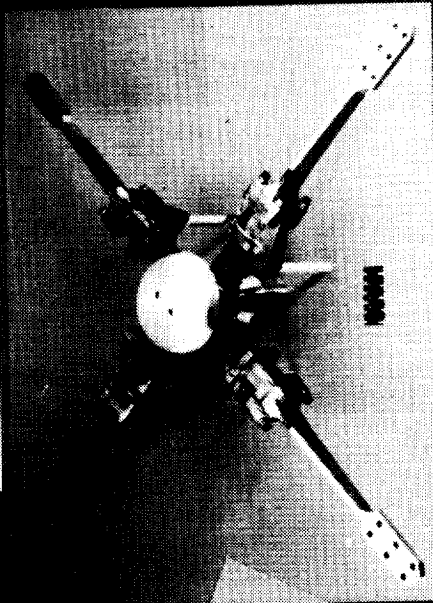
Figure 14 (a).

# AEROMECHANICAL STABILITY DATA BASE FOR PARAMETRIC HINGELESS ROTOR EXPANDED

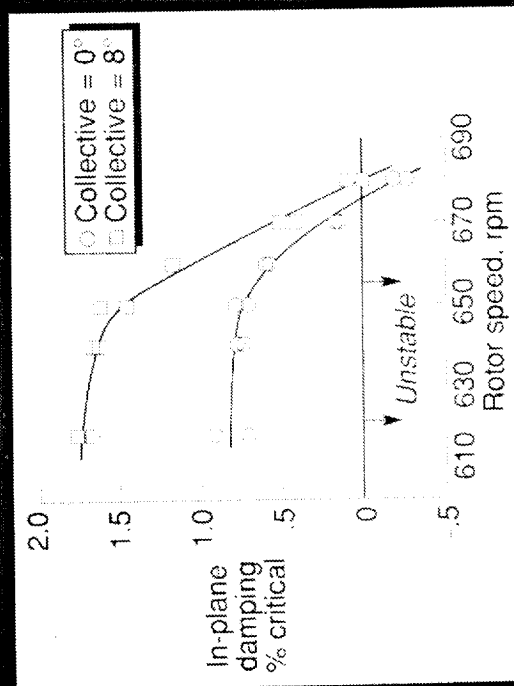
ARES with Hingeless Rotor Mounted in TDT



ARES Hingeless Hub



Hover



Forward Flight (Advance Ratio = 0.3)

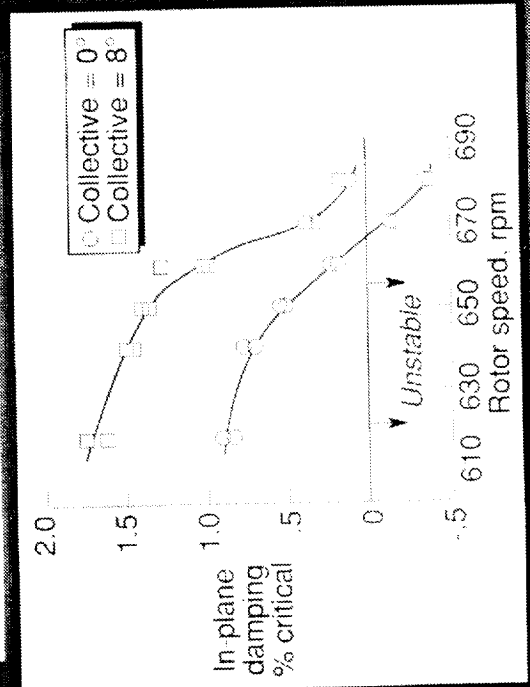


Figure 14 (b).

## MODIFICATIONS TO TRANSONIC DYNAMICS TUNNEL HEAVY GAS RECLAMATION SYSTEM IN PROGRESS

Bryce M. Kempley  
Configuration Aeroelasticity Branch

RTOP 505-63-50

**Research Objective:** The objective of this project is to improve the heavy gas recovery system at the Transonic Dynamics Tunnel (TDT) so that heavy gas losses are essentially eliminated. Reaching this goal will allow the TDT to resume normal operations as a highly functional test facility using heavy gas as the test medium.

**Approach:** Historically, the TDT has used heavy gas, namely dichlorodifluoromethane (R-12), as the test medium for approximately 95% of test operations since the early 1960's. Heavy gas is approximately four times heavier than air and has a speed of sound about half that of air. This is a significant advantage for testing aeroelastic models at transonic speeds because it allows use of heavier models, requires less tunnel fan horsepower, and provides higher Reynolds number test conditions. Heavy gas is stored as a liquid, vaporized into a gas for test purposes, and reclaimed into a liquid for storage and reuse. The existing heavy gas reclamation system, which is basically a three-stage refrigeration system, is to be replaced with a Low Temperature Condenser (LTC) system (fig. 15(b)). The LTC will utilize LN<sub>2</sub> as the cooling agent. Structural pockets in the plenum that trap heavy gas during the removal process will either be filled with cellular glass insulation or ported. Numerous items such as compressor seals, valves, and flanges will be replaced to minimize leaks. Where leaks might occur, a scavenger system will be used to capture and reinsert the heavy gases back into the processing system.

**Accomplishment Description:** Agency concern because of significant heavy gas losses at the TDT resulted in the decision in July 1989 to limit heavy gas operations to only those high priority tests (DoD) which were approved by the NASA Administrator on a case-by-case basis. Since then, a study and a total system design for the modified gas reclamation system have been completed. The design stipulates that all newly installed equipment must be compatible with known substitute gases that may be used in the future. Funds (CofF) have been approved for the project and a contract has been awarded for the construction phase with a scheduled completion of August 1991. Like any activity, there are always potential surprises. It was recognized early that a number of components to be removed were insulated with asbestos. All asbestos has been removed from those areas that would impact the project. The real surprise was finding Polychlorinated biphenyl (PCB's) on the interior surface of the TDT. Tests have shown that it is only a surface problem with no PCB's in the air. Cleansing techniques are being developed and tried on small areas to determine the best approach for full scale cleaning that is planned for April 1991.

**Significance:** The TDT should resume a full schedule, two-shift heavy gas operation in late 1991. Heavy gas losses are expected to be less than 1 ton per year.

**Future Plans:** Sulfur hexafluoride (SF<sub>6</sub>) has been identified as a replacement heavy gas for the TDT. It is environmentally acceptable and plans are to convert to SF<sub>6</sub> in F.Y. 1995.

Figure 15 (a).



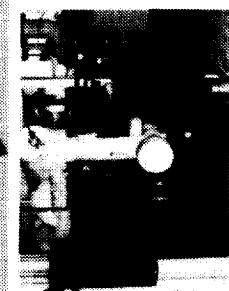
# MODIFICATIONS TO TRANSONIC DYNAMICS TUNNEL HEAVY GAS RECLAMATION SYSTEM IN PROGRESS

NEW LN<sub>2</sub> LTC  
Low Temperature Condenser System

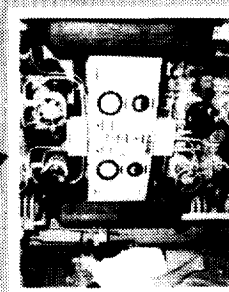
REPLACED BY  
LTC



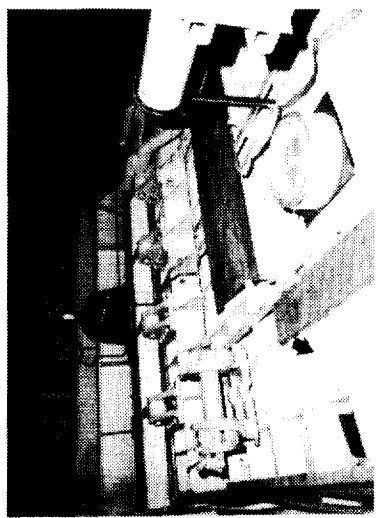
COOPER BESSEMER  
COMPRESSOR



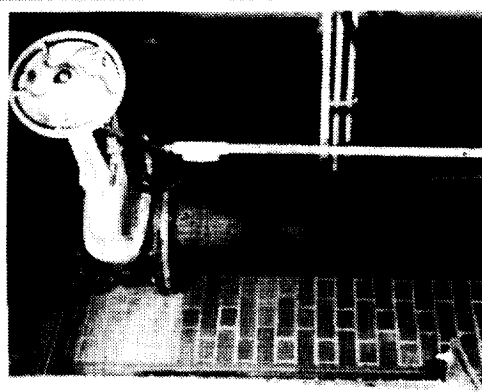
F-22 REFRIGERATION  
SYSTEM



DRYER 2



STRUCTURAL POCKETS TO BE FILLED  
(PLENUM/TEST SECTION)



TYPICAL VALVE AND FLANGE  
(UPGRADE REPLACEMENT)

Figure 15 (b).

## TDT DATA ACQUISITION SYSTEM IMPROVEMENTS IMPLEMENTED

David C. Rosser, Jr.  
Configuration Aeroelasticity Branch

RTOP 505-63-50

**Research Objective:** Testing of aeroelastic models, such as the AFW model shown in the upper left photo of figure 16(b), involves acquiring and analyzing large volumes of data in near real time to acquire information needed to guide continuation of testing. The objective of improving the Data Acquisition System at the Langley Transonic Dynamics Tunnel is to provide the test engineers with the tools needed to meet these near real time data analysis and display requirements, thus increasing the efficiency and safety of testing.

**Approach:** Based on operational experiences and projected research needs, several areas were identified where improvements were needed. The list of potential improvements include both hardware and software items. Two hardware improvements were implemented as well as two software programs for subcritical response analysis and a system of software programs for unsteady pressure measurements data acquisition and analysis.

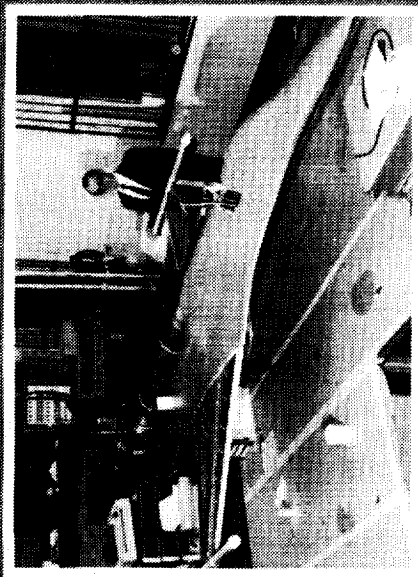
**Accomplishment Description:** Improvements were successfully accomplished in all areas that were identified. In the hardware area, two significant modifications were made to the analog/digital interface system. First, modified signal conditioning cards, shown in the lower left figure, which provided a significantly more convenient means for adjusting sensor excitation voltages and for setting shunt calibration resistors were designed, fabricated, checked, and then installed in the system. This modification substantially reduces the time required for initial instrumentation setup and for daily adjustments. Second, buffer amplifiers were added to eliminate variations of relative drift (time varying offsets) between analog and digital signals, thus eliminating the need for frequent adjustments of the analog signals. Several significant improvements were also made in the applications software area. Both Moving Block and Randomdec subcritical damping analysis techniques were added into the software capability of the current data acquisition system. The Moving Block analysis method is particularly attractive for use in the dynamic response and aeroelastic stability testing of helicopter models. The Randomdec subcritical damping technique is used for aeroelastic stability testing of airplane models. Also, a package of application software programs was developed for the current data acquisition system to acquire, analyze, and display steady and unsteady aerodynamic pressure data. Other less significant, but noteworthy, improvements were the addition of tunnel test condition information to video tape recordings of model motions and the acquisition of several new user interface terminals that provide forty (40) pages of non-volatile memory capability, thus decreasing down time associated with recovery from failure in other system components.

**Significance:** These hardware and software changes have provided significant improvements to the operational efficiency of the TDT data acquisition system and/or have provided the test engineers with significant added data acquisition, display, and analysis capabilities, thus improving data quality and providing for more efficient wind-on testing.

**Future Plans:** Activities will continue to focus on identifying and implementing improvements to the TDT data acquisition system that will increase efficiency, reliability, accuracy, and capability thus ensuring that the research capability of the TDT continues to be at the forefront of technology.

Figure 16 (a).

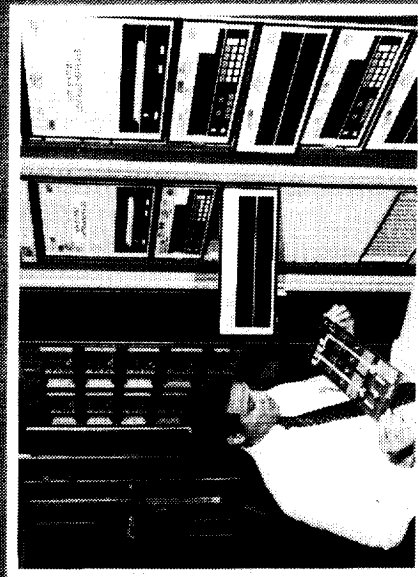
# TDT DATA ACQUISITION SYSTEM IMPROVEMENTS IMPLEMENTED



Typical Aeroelastic Model



Software Development Station



New Signal Conditioner Cards



New Control Room  
Computer Interface Terminals

Figure 16 (b).

# UNSTEADY AERODYNAMICS BRANCH

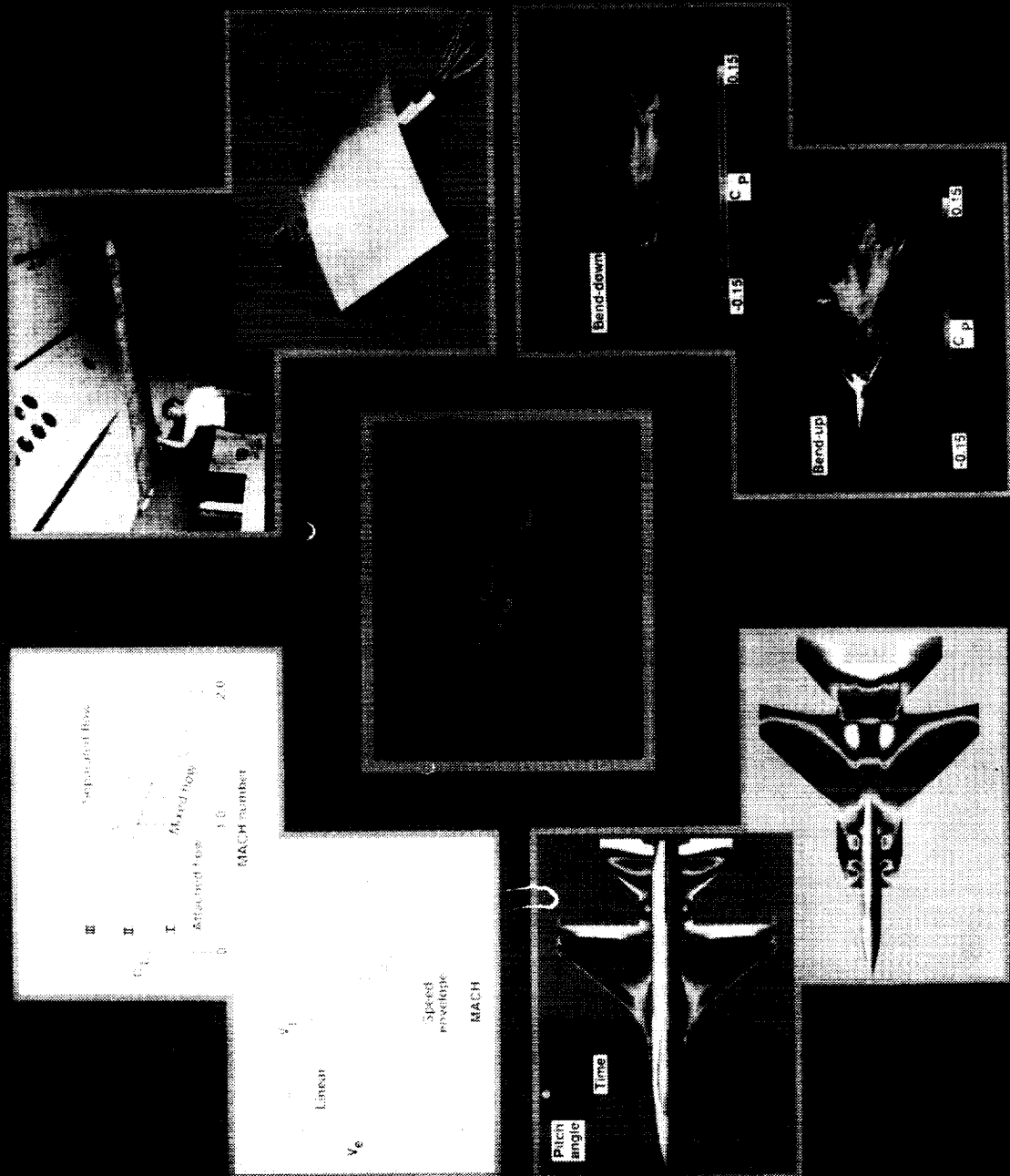


Figure 17.

ORIGINAL PAGE IS  
OF LOW QUALITY

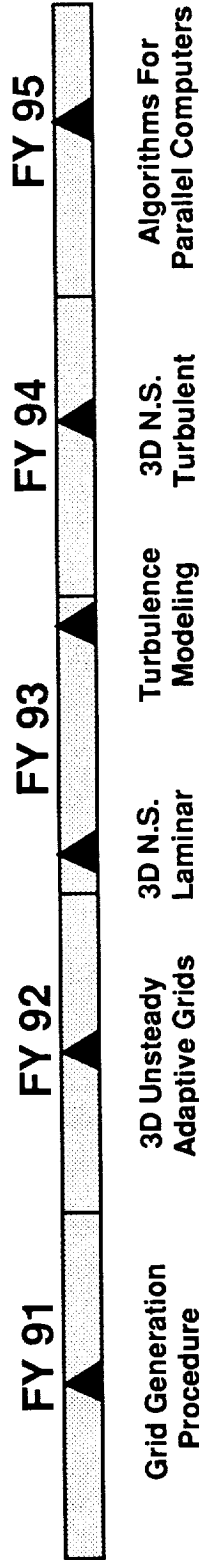
# UNSTEADY AERODYNAMICS FUTURE PLANS (FY 91-95)

## GOAL

DEVELOP, VALIDATE, AND APPLY UNSTRUCTURED-GRID, EULER/  
NAVIER-STOKES CODES FOR AIRCRAFT AEROELASTIC ANALYSIS

## KEY OBJECTIVES

### ● CONTINUED CODE DEVELOPMENT



### ● CODE APPLICATIONS

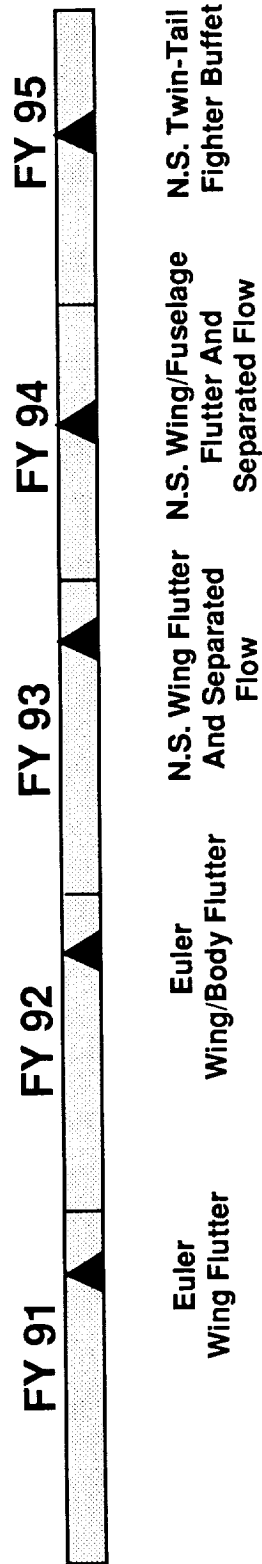


Figure 18 (a).

# UNSTEADY AERODYNAMICS FUTURE PLANS (FY 91-95)

GOAL

COMPLETE DEVELOPMENT, VALIDATE, AND APPLY TSD CODE FOR AIRCRAFT AEROELASTIC ANALYSIS

KEY OBJECTIVES

- CAP-TSD CODE MODIFICATIONS

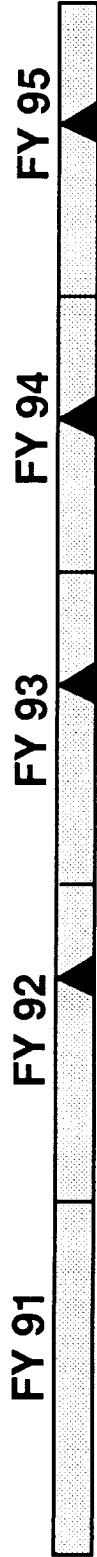


Vertical Tails  
Flexible Bodies

Inverse  
Boundary Layer

User's Guide

- CAP-TSD APPLICATIONS



NASP  
Transonic Flutter

Aileron Buzz

Wing-Store  
LCO

Advanced  
Fighter Config

Figure 18 (b).

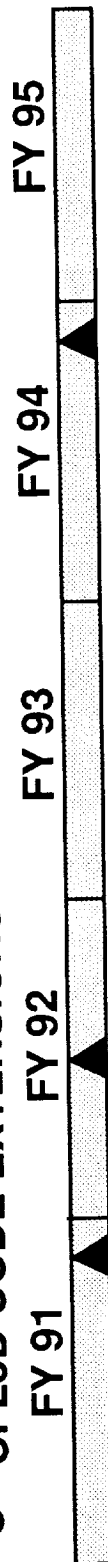
# UNSTEADY AERODYNAMICS FUTURE PLANS (FY 91-95)

## GOAL

DEVELOP, VALIDATE, AND APPLY STRUCTURED-GRID, EULER/  
NAVIER-STOKES CODES FOR AIRCRAFT AEROELASTIC ANALYSIS

## KEY OBJECTIVES

- CFL3D CODE EXTENSIONS



Vertical Tails    Real Gas Effects  
Flexible Bodies

User's Guide

- CFL3D AND ENS3DAE CODE APPLICATIONS



Acquire ENS3DAE

NASP Hypersonic  
Flutter

Wing Flutter &  
Separated Flow

Wing/Fuselage  
Flutter &  
Separated Flow

Twin-Tail  
Fighter Buffet

Figure 18 (c).

# HISAIR VEHICLE AIRLOADS PREDICTED USING CAP-TSD CODE

James T. Howlett  
Unsteady Aerodynamics Branch

RTOP 505-63-50

**Research Objective:** The objective of this research is to investigate the capabilities of non-linear CFD theories to provide improved unsteady aerodynamic analyses for complex, blended wing/body configurations, including the modeling of highly swept wing planforms, multiple control surfaces, and wing/body interference effects.

**Approach:** The CAP-TSD (Computational Aeroelasticity Program - Transonic Small Disturbance) computer code will be used to analyze the unsteady transonic aerodynamics for a fully three-dimensional analytical model of the HISAIR vehicle. The analytical model will include the vehicle body, wing thickness, twist, dihedral, and control surfaces. Aeroelastic calculations will be performed using mode shapes supplied by the structural analysts in order to determine a flutter boundary.

**Accomplishment Description:** The HISAIR vehicle has been analytically modeled both as a flat plate and as a wing with thickness, twist, and dihedral. As shown by the sketch in the upper left side of figure 19(b), both of these models include control surfaces. The plot on the upper right side of the figure shows the steady lifting pressure distribution for the thick wing model at  $M = 0.7$  and  $\alpha = 0^\circ$ . As the plot indicates, the lifting pressure is low over the highly swept inboard section of the wing and increases significantly on the outboard section. The effect on the lift and moment coefficients of individually deflecting the flaps  $1^\circ$  is shown on the plot in the lower left side of the figure. The inboard trailing edge flap has the largest effect on both the lift and the moment and the effect of the leading edge flap is minimal. The plot on the lower right side of the figure shows a comparison of the incremental forces for the flat plate model and the thick wing model. Although the lifting forces are very different for the two models, the incremental forces due to control surface deflection are nearly the same, verifying known results for control surface effects and validating the analytical model.

**Significance:** The results indicate that the CAP-TSD computer code can be used to calculate the aerodynamic loads on the highly swept wing planform of the HISAIR vehicle. In addition, the effect on these loads of control surface deflections can be investigated. This suggests that the method can be applied to investigate aeroelastic effects which may be significant for the HISAIR vehicle.

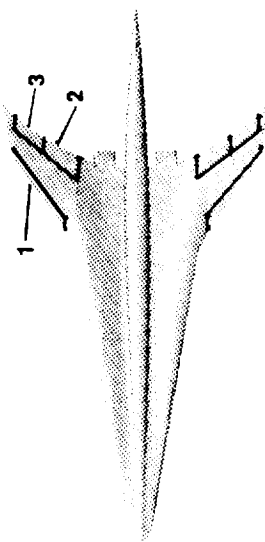
**Future Plans:** The analytical model will be updated to include the fuselage, calculations will be performed in the nonlinear transonic range, and aeroelastic calculations will be done to determine a flutter boundary.

Figure 19 (a).

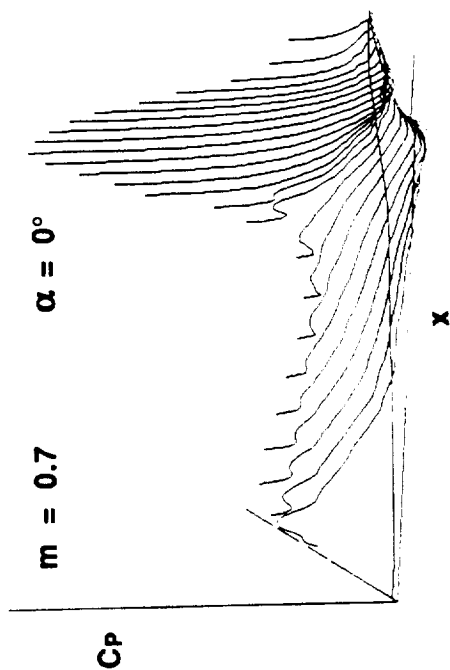


# HISAIR VEHICLE AIRLOADS PREDICTED USING CAP-TSD CODE

Planform with Control Surfaces



Lifting Pressure Distribution



EFFECT OF 1 DEG FLAP DEFLECTION -  $M = 0.7$

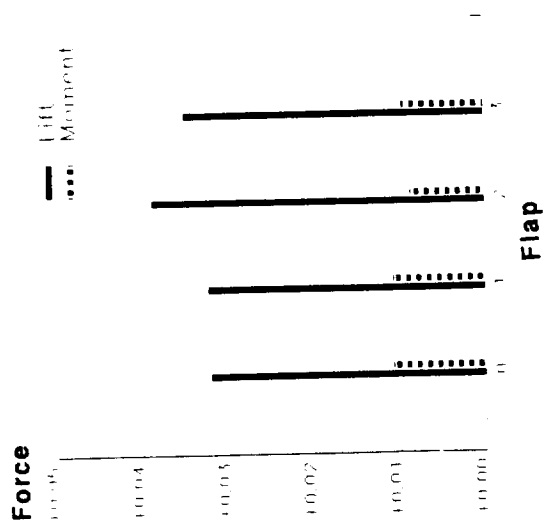
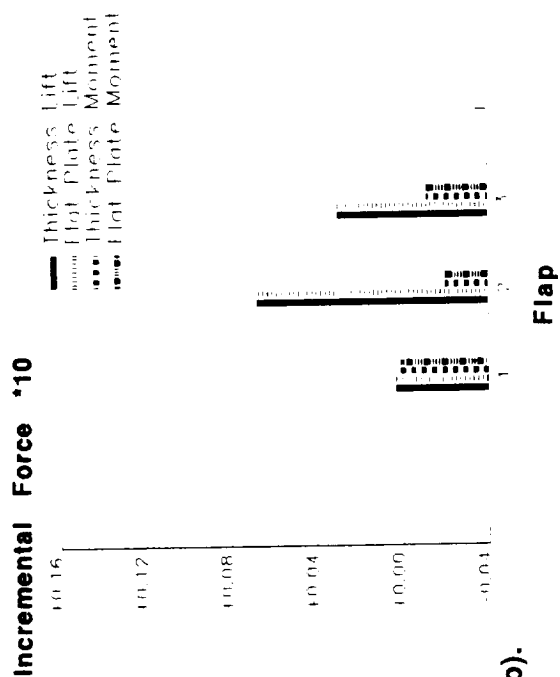


Figure 19 (b).

INCREMENTAL FORCE COMPARISON -  $M = 0.7$



# THE VOLTERRA-WIENER THEORY OF NONLINEAR SYSTEMS APPLIED TO THE MODELING OF NONLINEAR AERODYNAMIC RESPONSES USING CAP-TSD

Walter A. Silva  
Unsteady Aerodynamics Branch

RTOP 505-63-50

**Research Objective:** Modern aeroservoelastic analysis methods model linear aerodynamic response as an approximate linear system (rational function approximation) that augments the structural portion of the equations of motion. There is, however, a very real need to perform aeroservoelastic analyses in the transonic regime where dynamic instabilities can be very severe and sudden. Transonic aerodynamics are nonlinear and cannot accurately be approximated using linear methods. The objective of this research is to develop a methodology to model nonlinear aerodynamic response using the Volterra-Wiener theory of nonlinear systems for subsequent use in aeroservoelastic analysis.

**Approach:** The basic premise of the Volterra-Wiener theory of nonlinear systems is that any nonlinear system can be modeled by an infinite sum of subsystems of increasing order. These subsystems contain a kernel that describes the behavior of the system at that order (see figure 20 (b)). The first order kernel is simply the linear unit impulse response of the system which assumes that the response of the system at a given time  $t$  is independent of the response is valid for linear systems. The second-order kernel is the response of the system to two unit impulse responses at different time intervals. This is a measure of the relative influence of a previous input on the current response, which is a measure of nonlinearity. The current research will be limited to a second-order formulation. The second-order kernel is computed using the pulse response option within CAP-TSD (Computational Aeroelasticity Program - Transonic Small Disturbance) code for two pulses at varying time intervals. Once the kernel has been computed, a bilinear state-space realization of the system can be analytically obtained, analogous to the linear realization obtainable from the unit impulse response of a linear system.

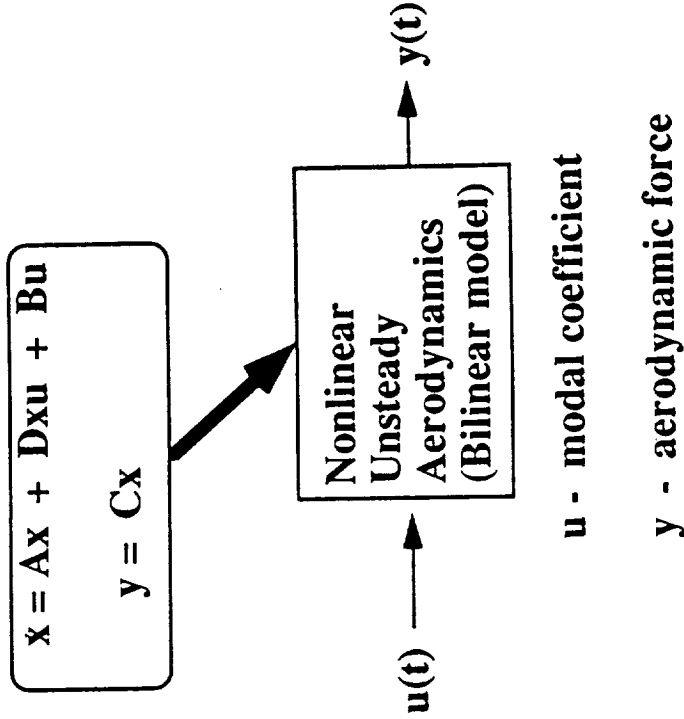
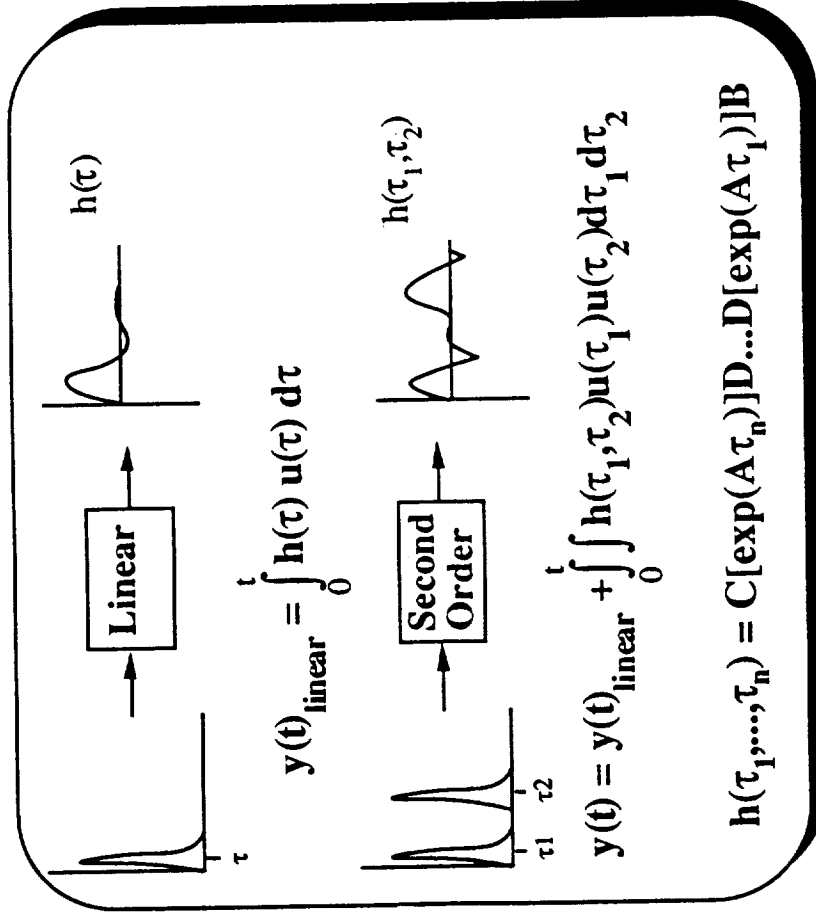
**Accomplishment Description:** Identification of the second-order kernel was performed on a simple, nonphysical bilinear system using unit pulse responses. The numerically identified kernel compares well with the exact analytically defined second-order kernel. Currently, this identification technique is being applied to a rectangular wing with a NACA 0021 airfoil using the CAP-TSD code in order to identify the second-order kernel at transonic Mach numbers.

**Significance:** Once a second-order kernel is identified at a given transonic Mach number and condition, the nonlinear response of the aerodynamic system to an arbitrary input can be predicted. In addition, a bilinear state-space system can be realized that models the nonlinear aerodynamic response. This bilinear state-space system can then be used in aeroservoelastic analyses.

**Future Plans:** Other, more sophisticated identification techniques will be applied that would improve the accuracy of the second-order kernel and thus of the nonlinear aerodynamic model. This technique will also be applied to a complete aeroservoelastic problem for further verification of the approach.

Figure 20 (a).

# The Volterra-Wiener Theory of Nonlinear Systems Applied to the Modeling of Nonlinear Aerodynamic Responses Using CAP-TSD



- Kernels evaluated numerically by multidimensional impulse responses
- Truncated series converted to bilinear state-space realization
- Directly usable in existing ASE evaluation methods

Figure 20 (b).

# EFFECTS OF FINITE-DIFFERENCE MESH AND TIME STEP IN SOLUTION OF THE TRANSONIC SMALL DISTURBANCE EQUATION

Samuel R. Bland  
Unsteady Aerodynamics Branch

RTOP 505-63-50

**Research Objective:** The objective is to guide the selection of finite-difference meshes and time step sizes for the time accurate unsteady flow calculations needed in aeroelastic analysis.

**Approach:** A one-dimensional equation is used to model the wave propagation of the complete Transonic Small Disturbance (TSD) equation. Analysis of the difference scheme and discretization used confirms the numerical results.

**Accomplishment Description:** Inaccurate solutions of the TSD equation are known to arise from inadequate treatment of the disturbances propagating outward from the vehicle through the finite-difference mesh. This effect is simulated in the present study by solving the equation for wave motion in the vertical direction with the algorithm used in the CAP-TSD (Computational Aeroelasticity Program - Transonic Small Disturbance) code. Analysis of the difference equations predicts reflections of the outgoing wave that arise from both the stretching of the mesh and the simulated far field boundary. This study has guided the choice of mesh stretching to minimize the internal reflections and has shown the necessity for finer meshes in the far field to avoid the nonphysical reflections.

These effects are illustrated in the first two parts of figure 21(b). The illustrations on the left show the time history of the response at the wing to a pulse in downwash. The figures on the right give the magnitude of the Fourier transform of this response as a function of frequency in the range of interest for flutter. The top illustration is for an original mesh which has good properties for minimizing internal reflections but is not fine enough in the far field to eliminate a small boundary reflection. This reflection evidences itself at time 44, the time it takes for the pulse centered at time 4 to travel to the far boundary (20 chord-lengths away) and return. This boundary reflection contaminates the response at low frequencies. A much better result is obtained using a new mesh designed during this study and shown in the second illustration. Fine spacing in the far field eliminates the low frequency boundary reflection error. Both of these results use a time step of about 0.24. The results for a time step half as large are shown in the lower two figures. The solution on the original mesh contains errors at all frequencies. Although the time history for the new mesh looks worse, errors occur at frequencies above one and might not be serious for flutter calculations.

Analysis shows that the solution of the discrete equations contains an error which occurs at a frequency of one over the mesh spacing and becomes more of a problem as the time step is reduced. Each mesh has a maximum spacing of 1.0; a frequency of one appears to be a critical value. Both meshes have spacings of 0.013 at the wing surface and they use 40 and 37 points, respectively.

**Significance:** This study has provided guidelines for the design of improved meshes and has led to a mesh design code documented for use with CAP-TSD. Insight has been obtained into problems encountered with TSD codes as time step is reduced.

**Future Plans:** The techniques developed for TSD theory are being applied to the more exact Euler and Navier-Stokes equations.

Figure 21 (a).

# CHOICE OF FINITE-DIFFERENCE MESH AND TIME STEP IN SOLUTION OF THE TRANSONIC SMALL DISTURBANCE EQUATION

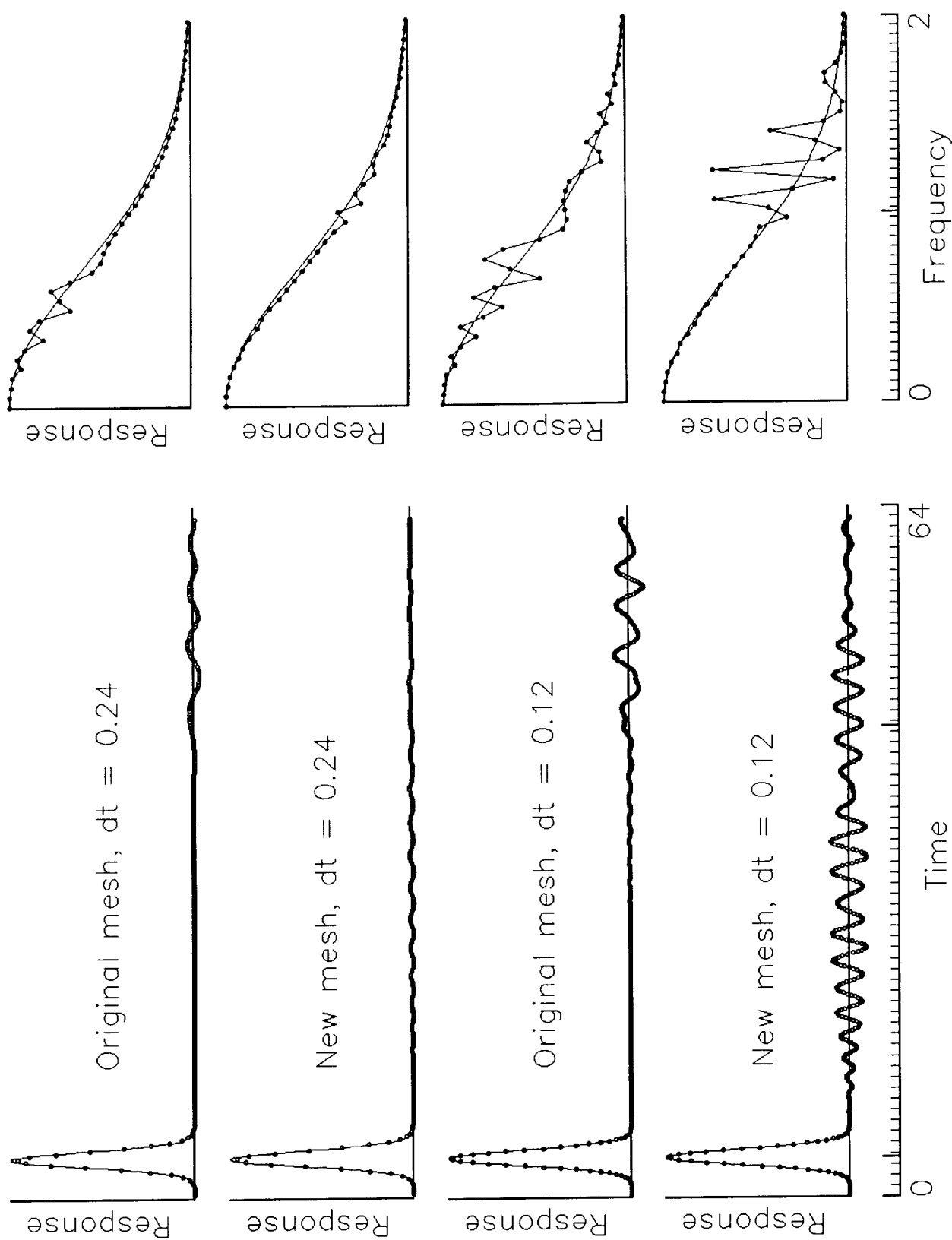


Figure 21 (b).

# CONICAL EULER METHOD DEVELOPED TO STUDY UNSTEADY VORTICAL FLOWS ABOUT ROLLING DELTA WINGS

Elizabeth M. Lee and John T. Batina  
Unsteady Aerodynamics Branch

RTOP 505-63-50

**Research Objective:** The objective of the research is to develop the conical Euler methodology to efficiently investigate unsteady vortical flows about highly-swept delta wings undergoing forced harmonic rolling oscillations and to determine the free-to-roll response characteristics of such wings including the so-called wing rock phenomenon.

**Approach:** Modifications were made to a conical Euler code to allow for the additional analysis of the free-to-roll motions of a delta wing. The code employs a multistage Runge-Kutta time stepping scheme which uses a finite-volume spatial discretization on an unstructured mesh of triangles. The modifications added a free-to-roll capability by the inclusion of the rigid-body equation of motion for its simultaneous time integration with the governing flow equations.

**Accomplishment Description:** Calculations were performed for a  $75^\circ$  swept delta wing at a freestream Mach number of 1.2 and an angle of attack of  $\alpha = 30^\circ$ . A partial view of the crossflow grid which was used is shown in the upper left part of figure 22(b). The grid indicates that the wing has thickness and sharp leading edges. Steady-state results were obtained to determine the basic character of the vortical flow. Total pressure loss contours from this calculation, shown in the upper right part of the figure, indicate that the flow separates from each of the leading edges producing large circular vortices. The delta wing was then forced to oscillate harmonically in roll at a reduced frequency of  $k = 0.3$ . Two amplitudes of motion,  $\Delta\phi = \pm 5^\circ$  and  $\pm 35^\circ$ , were considered. The resulting rolling moment coefficients versus roll angle,  $\phi$ , are shown in the lower left part of the figure. For the smaller amplitude of  $\pm 5^\circ$ , the results show a clockwise-oriented loop which will produce a divergent (unstable) response if the wing were allowed to be free to roll. At  $\Delta\phi = \pm 35^\circ$ , however, the moment coefficient has counter clockwise-oriented loops at the extremes of the motion which have a stabilizing effect on the free-to-roll response. Finally, shown in the lower right part of the figure is the free-to-roll response. The curve indicates that initially the oscillatory response diverges for small values of the roll angle and then the response reaches a maximum amplitude of motion corresponding to a limit cycle.

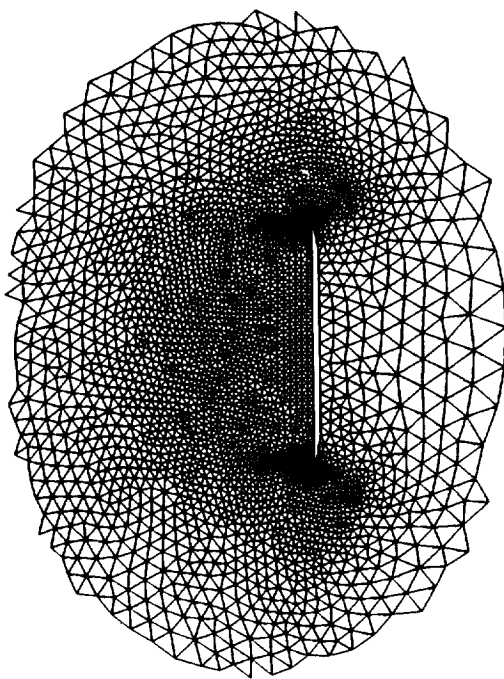
**Significance:** The limit cycle oscillation is indicative of a phenomenon called wing rock which occurs for very highly swept delta wings at high angles of attack. These results demonstrate the ability of the conical Euler methodology to predict this type of vortical flow phenomenon.

**Future Plans:** Further calculations will be performed to determine the flow mechanisms responsible for wing rock.

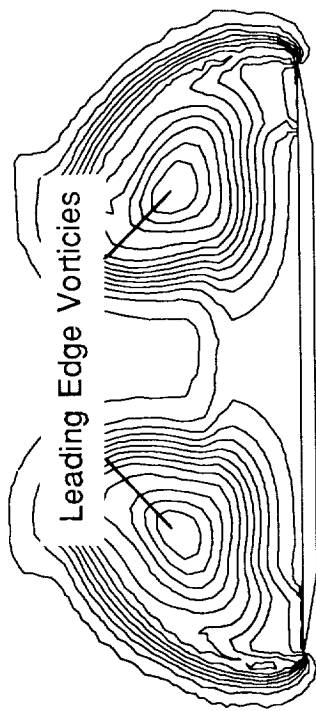
Figure 22 (a).

# CONICAL EULER METHOD DEVELOPED TO STUDY UNSTEADY VORTICAL FLOWS ABOUT ROLLING DELTA WINGS

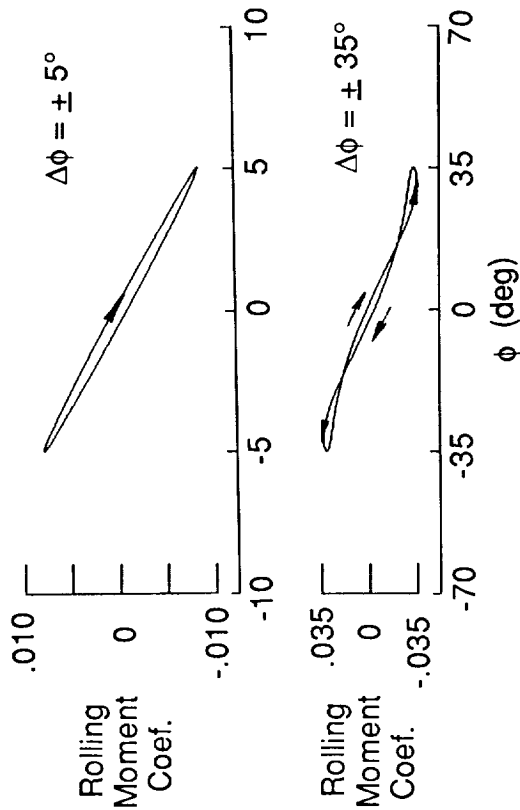
- Grid about 75° delta wing



- Total pressure loss at  $M_\infty = 1.2$  and  $\alpha = 30^\circ$



- Forced harmonic rolling



- Free-to-roll (wing rock)

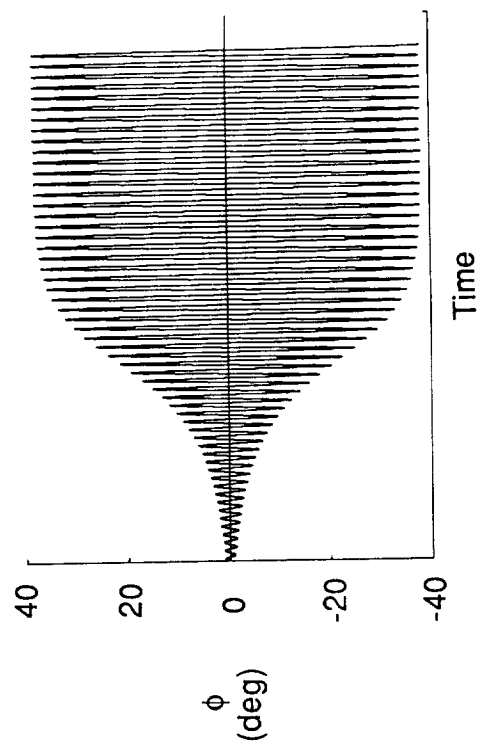


Figure 22 (b).

# UNSTEADY FLOW AROUND DELTA WINGS WITH SYMMETRIC AND ASYMMETRIC LEADING-EDGE FLAPS OSCILLATIONS

Professor Osama A. Kandil and Mr. Ahmed A. Salman  
Old Dominion University

RTOP 505-63-50

**Research Objective:** The major objective of this research work is to study the effect of symmetric and asymmetric oscillations of the leading-edge flaps of a delta wing. This includes the vortex-shock interaction and its subsequent effect on the aerodynamic loads. The frequency and amplitude of oscillation and the hinge location are some of the parameters to be investigated. The dynamics of the wing and its flaps is also included in this study.

**Approach:** The fluid dynamics portion of the problem is solved using the unsteady, compressible Navier-Stokes equations for the flowfield vector and the linearized unsteady Navier-displacement equations for the grid displacements due to the flap motion. The computer program which is used for the solution is called "ICF3D". The Euler equations of motion for the wing and its flaps are used to solve for the motion of the wing and/or flaps in order to include their dynamical effects. The problem can be solved due to prescribed motion without the dynamics effect or due to initial conditions including the dynamics effect.

**Accomplishment Description:** A sample computation for a locally-conical, unsteady flow around a sharp-edged delta wing due to asymmetric oscillation of the flaps is shown in figure 23(b). The flap hinge is located at the 75% local semi-span station. The flap is forced to oscillate harmonically at a reduced frequency of  $\pi$  and an amplitude of  $10^\circ$ . The flow periodic response is reached in the third cycle of oscillation. The figure shows the total-pressure-loss contours on one side of the wing at four snapshots of  $\delta = 0^\circ, 10^\circ, 0^\circ, -10^\circ$ . The details of the motion of the primary vortex, secondary vortex, tertiary vortex and the shock under the primary vortex are clearly demonstrated.

**Significance:** The present formulation and computational codes can treat unsteady vortex-dominated flow problems around rigid and flexible delta wings including their dynamical response.

**Future Plans:** Three-dimensional unsteady flows around rigid and flexible delta wings are currently investigated. Three applications are under consideration. The first application is for a pitching delta wing which undergoes a bending mode. The second application is for the dynamics/aerodynamics response of a delta wing which undergoes a rocking motion in the vortex breakdown range. The third application is for buffeting of a vertical tail in a vortex breakdown flow.

Figure 23 (a).

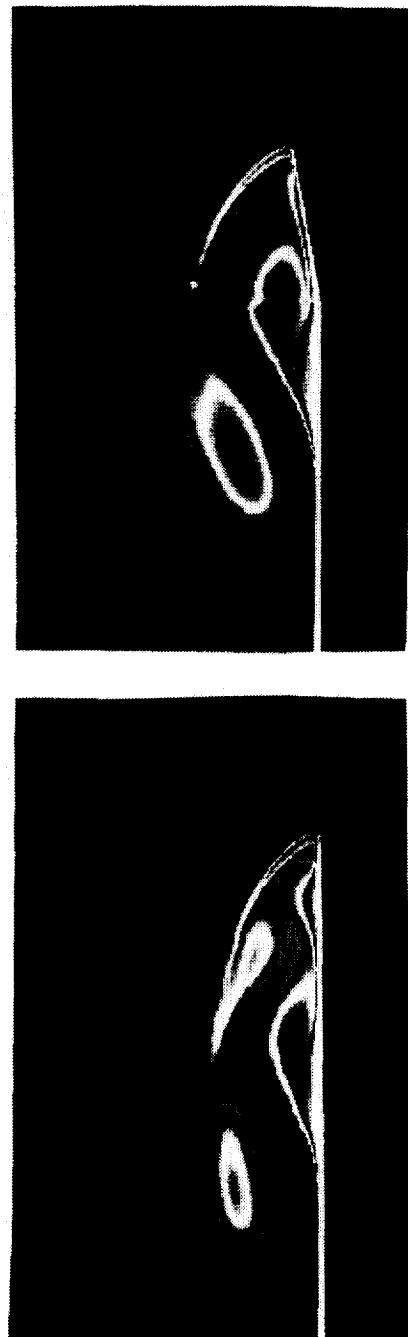


# EFFECT OF FLAP OSCILLATION ON LEADING-EDGE VORTEX-SHOCK FLOW

$M_\infty = 1.5$ ,  $M_N = 1.5$ ,  $R_\delta = 0.5 \times 10^6$ ,  $264 \times 90$  grid points

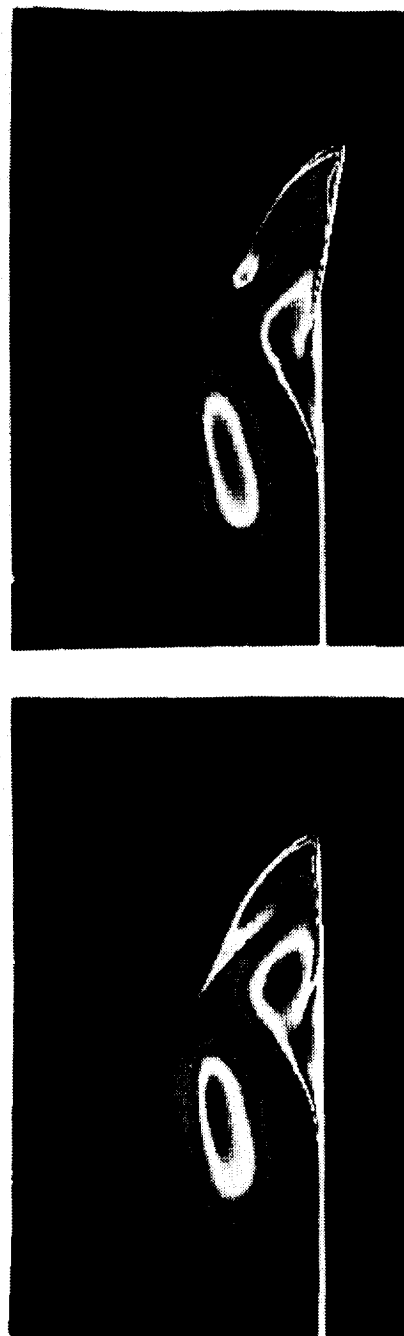
$\delta = \delta_{\max} \sin kt$ ,  $\delta_{\max} = 10^\circ$ ,  $k = \pi$ ,  $\Delta t = 0.25 \times 10^{-3}$

Total-Pressure-Loss Contours



(1)  $\delta = 0$ ,  $n = 16,000$

(2)  $\delta = 10^\circ$ ,  $n = 18,000$



(3)  $\delta = 0$ ,  $n = 20,000$

(4)  $\delta = -10^\circ$ ,  $n = 22,000$

Figure 23 (b).

## CFD SIMULATES ACTIVE CONTROL OF DELTA WING ROCKING MOTION

Elizabeth M. Lee and John T. Batina  
Unsteady Aerodynamics Branch

RTOP 505-63-50

**Research Objective:** The objective of the research is to demonstrate that the limit-cycle wing-rocking motion of a highly swept delta wing, which was calculated with a conical Euler code, can be actively suppressed through the use of a rate-feedback control law and antisymmetrically-deflected leading edge flaps.

**Approach:** Modifications were made to an unstructured grid conical Euler code to allow for the application of a rate-feedback control law to leading-edge flaps on the delta wing. The modifications included the addition of a control law in the simultaneous time integration of the rigid-body roll equation with the governing flow equations. A deforming mesh algorithm was also included to deform the mesh about the deflected leading-edge flaps. The advantages of using unstructured grid methods for this type of problem are that unstructured meshes allow an efficient refinement of the mesh on the leeward side of the delta wing where dominant flow features are expected to occur and also that the deforming mesh algorithm can be applied very easily and efficiently to these types of meshes.

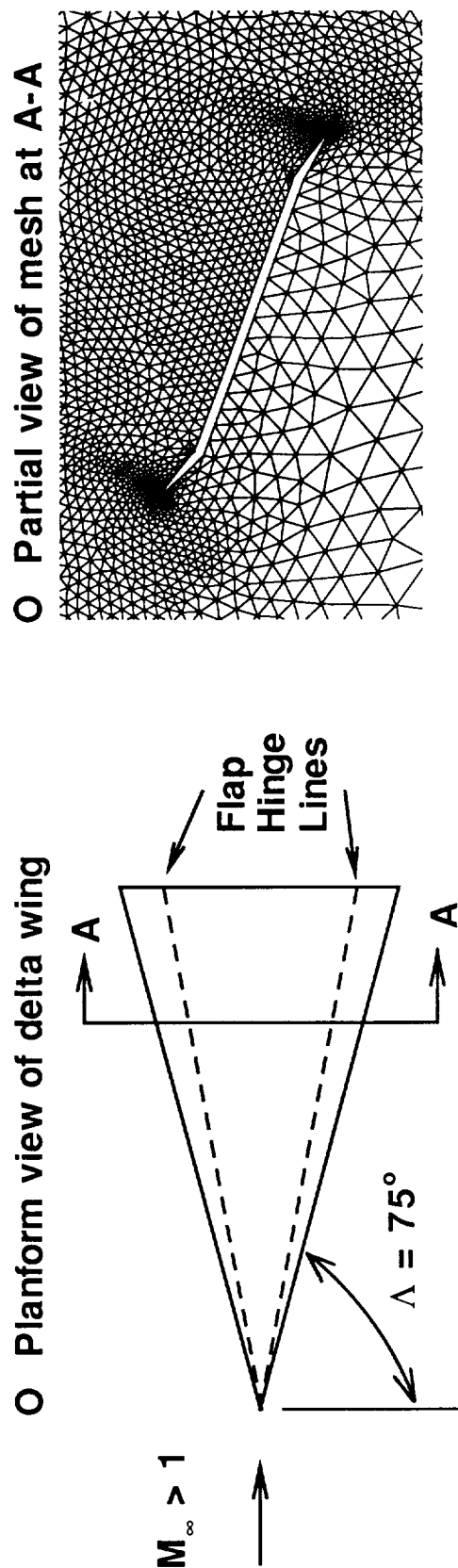
**Accomplishment Description:** Calculations were performed for a  $75^\circ$  swept delta wing at a freestream Mach number of  $M_\infty = 1.2$  and an angle of attack of  $\alpha = 30^\circ$ . A planform view of this delta wing is shown in the upper left part of figure 24(b). The leading-edge flap is approximately 28% of the local semi-span. A partial view of the crossflow grid at section AA is shown in the upper right part of the figure. The wing was rolled  $30^\circ$  and the flaps were deflected  $10^\circ$  to illustrate how the mesh can deform so that it conforms continuously to the instantaneous position of the wing. Note that the deforming mesh algorithm deforms the mesh smoothly about the deflected leading edge flaps as the wing undergoes the rolling motion. The free-to-roll response due to an initial small angular velocity perturbation was computed both with and without active control. Plots of the free response time history for both cases are shown in the lower part of the figure. Note the different scaling on the vertical axes. Without active control, the roll response diverges initially at the smaller roll angles, but as the amplitude of motion grows with time, the response transitions to a wing-rock type of limit-cycle oscillation. With active control included the roll response converges to its initial steady state value after the same small perturbation, and thus the wing rocking motion is suppressed.

**Significance:** The results demonstrate the ability of the conical Euler methodology to simulate the active suppression of a wing-rocking motion of a highly swept delta wing.

**Future Plans:** Continue the study of unsteady vortex dominated flows using computational fluid dynamics.

Figure 24 (a).

# CFD SIMULATES ACTIVE CONTROL OF DELTA WING ROCKING MOTION



Free-to-roll response at  $M_\infty = 1.2$  and  $\alpha = 30^\circ$

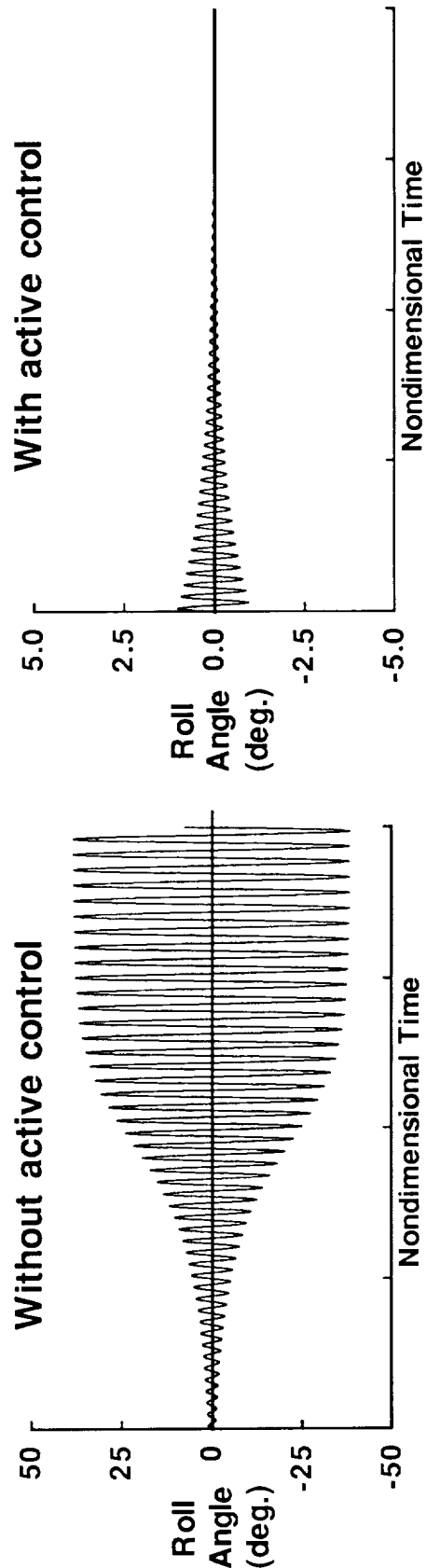


Figure 24 (b).

# AUTOMATED SPATIAL ADAPTION PROCEDURE DEVELOPED FOR ACCURATE UNSTEADY FLOW ANALYSIS

Russ D. Rausch  
Purdue University

and

John T. Batina  
Unsteady Aerodynamics Branch

RTOP 505-63-50

**Research Objective:** The objective of the research is to develop an automated spatial adaption procedure to implement within an Euler code for the accurate and efficient computation of unsteady flows.

**Approach:** Modifications were made to a two-dimensional unstructured-grid upwind-type Euler code to include procedures for mesh enrichment and mesh coarsening to either add points in high gradient regions of the flow or remove points where they are not needed, respectively, to produce solutions of high spatial accuracy at minimal computational cost. The modifications included adding mesh enrichment and coarsening procedures as well as a parametric spline routine to locate new points that lie on boundaries. The advantage of using a spatial adaption procedure is that the solution dictates the mesh topology for an efficient computation.

**Accomplishment Description:** Calculations were performed for a normal shock moving from left to right at a Mach number of  $M_s = 2.81$  which impinges on a half cylinder. The problem was selected to test the adaption procedures by studying the resulting transient shock wave diffraction phenomena and comparing computed time dependent solutions with experimental data. Computed density contours are shown in the upper left part of the figure 25(b) at three moments in time. The density contours give a reasonable representation of the flow and the subsequent development of the diffraction process that covers regular reflection, transition to Mach reflection, and shock-on-shock interaction. A schlieren photograph from the experiment is shown in the upper right part of the figure. Computed density contours are shown at the same moment in time in the lower right part of the figure where the incident shock, shock triple point, reflected shock, and contact discontinuity are identified. The lower left part of the figure contains the instantaneous mesh at the same moment in time. Here points have been added to regions of the flow where the density is changing rapidly. Note the region near the front of the cylinder where the density gradients are relatively small and the points are being removed for computational efficiency.

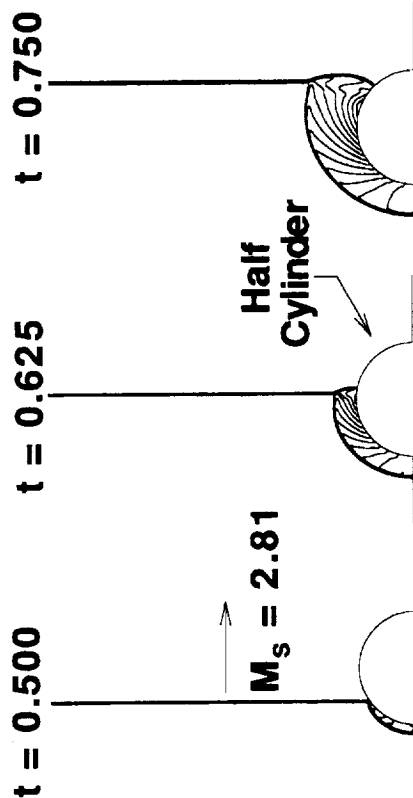
**Significance:** The results demonstrate the ability of the automated spatial adaption procedures to add and remove points during an unsteady flow computation to accurately and efficiently resolve transient flow features.

**Future Plans:** Future plans are to develop mesh enrichment and mesh coarsening procedures for a three-dimensional unstructured-grid upwind-type Euler code to be used for unsteady aerodynamic and aeroelastic analyses of complete aircraft configurations.

Figure 25 (a).

# AUTOMATED SPATIAL ADAPTION PROCEDURE DEVELOPED FOR ACCURATE UNSTEADY FLOW ANALYSIS

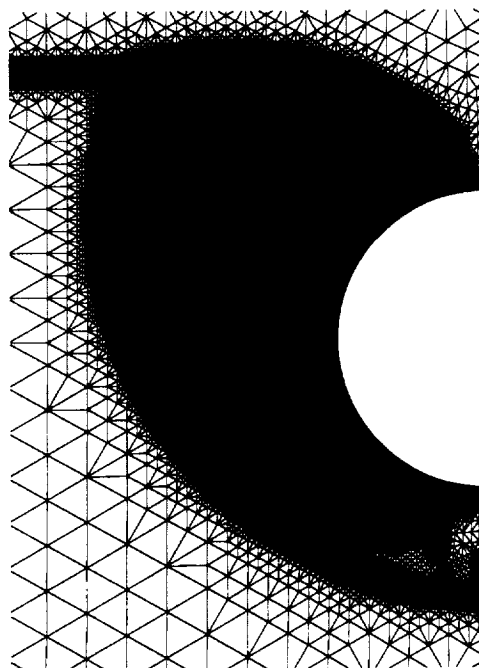
- Transient Shock Problem



- Experimental Density Variation



- Instantaneous Mesh



- Computed Density Contours

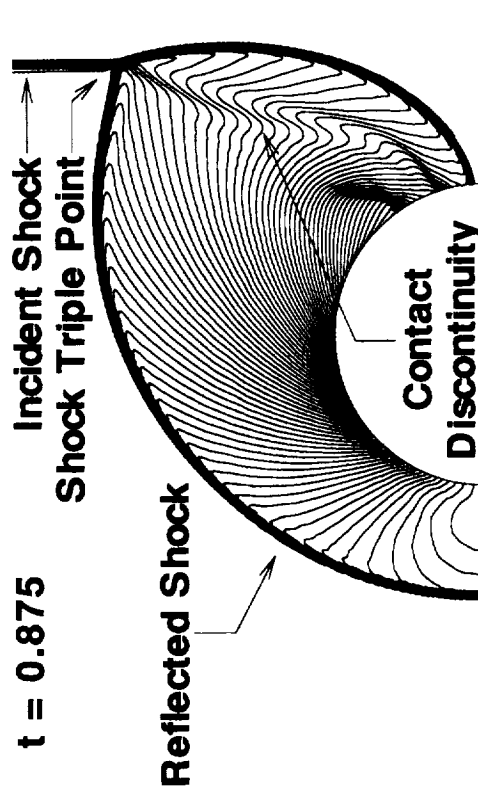


Figure 25 (b).

# THREE-DIMENSIONAL FLUX-SPLIT EULER ALGORITHM FOR UNSTRUCTURED GRIDS VALIDATED FOR STEADY FLOW

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RTOP 505-63-50

**Research Objective:** New algorithms are being developed for the solution of the three-dimensional unsteady Euler equations based on the use of unstructured grids. These algorithms require validation before they may be used with confidence for general applications. The objective of this research, therefore, was to determine the accuracy of a new flux-split method of solving the Euler equations on an unstructured grid of tetrahedra.

**Approach:** The new algorithm involves improvements that have been developed recently to the spatial and temporal discretizations used by unstructured grid flow solvers. The spatial discretization now involves a flux-split approach which is naturally dissipative and captures shock waves sharply with only one grid point within the shock structure. The temporal discretization involves either explicit or implicit time-marching. The explicit time-marching is a four-stage Runge-Kutta integration and the implicit time-marching is a two sweep Gauss-Seidel relaxation procedure. The algorithm is validated by performing calculations using the explicit integration for a well-defined wing case which is an AGARD standard configuration and making comparisons with experimental steady pressure data.

**Accomplishment Description:** To assess the accuracy of the new three-dimensional flux-split Euler solver, calculations were performed for the ONERA M6 wing. The M6 wing has a leading edge sweep angle of  $30^\circ$ , an aspect ratio of 3.8, and a taper ratio of 0.562. The airfoil section of the wing is the ONERA "D" airfoil which is a 10% maximum thickness-to-chord ratio conventional section. The results were obtained using a grid which has 154,134 nodes and 869,056 tetrahedra. The surface triangulation for the upper surface of the wing is shown in the left half of the figure. Results were obtained for the M6 wing at a freestream Mach number of 0.84 and  $3.06^\circ$  angle of attack. These conditions were chosen for comparison with experimental pressure data as shown in the right half of figure 26(b). The results indicate that there is a weak supersonic-to-supersonic shock wave near the leading edge on the inboard portion of the wing. The primary, supersonic-to-subsonic shock which occurs in the midchord region coalesces with the first shock in the outboard direction toward the wing tip. Near the tip, the two shocks merge to form a single, strong, supersonic-to-subsonic shock wave. Because of the large number of tetrahedra used in this case, the solution required 150 Cray-2 CPU hours and 125 megawords of memory.

**Significance:** The Euler results are in good agreement with the experimental pressure data, especially in predicting the strength and location of the shock waves, which tends to verify the new Euler algorithm. The shocks are sharply captured with only one grid point within the shock structure and there are no overshoots or undershoots.

**Future Plans:** The accuracy as well as efficiency of the new flux-split algorithm will be determined for unsteady flows.

Figure 26 (a).

# INITIAL VALIDATION OF THREE-DIMENSIONAL FLUX-SPLIT EULER ALGORITHM FOR UNSTRUCTURED GRIDS ACCOMPLISHED

- Total grid has 154,314 nodes and 869,056 tetrahedra
- Comparison with experiment at  $M_\infty = 0.84$  and  $\alpha = 3.06^\circ$

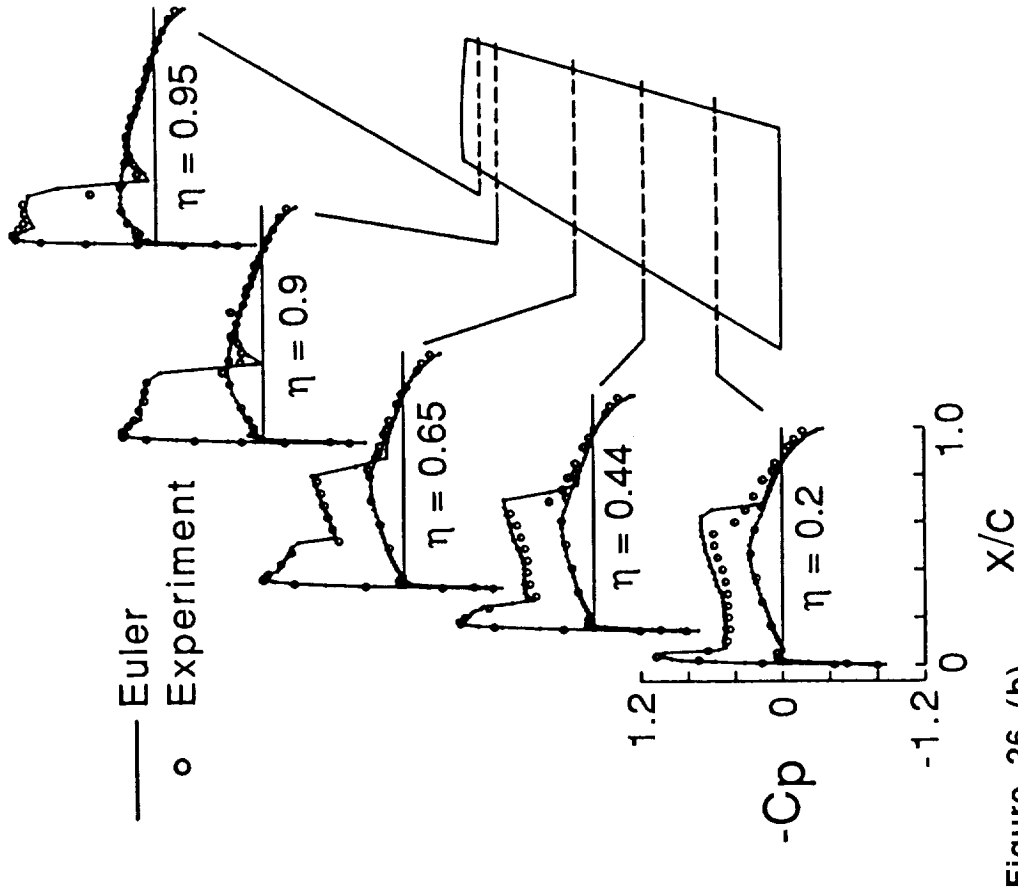
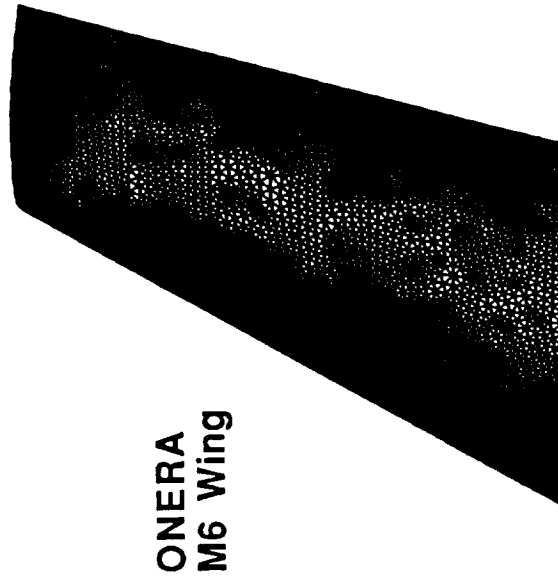


Figure 26 (b).

- Resource requirements:  
150 hours Cray-2 CPU time  
125 megawords memory

## GRAPHICS CODE DEVELOPED TO PERMIT VISUALIZATION OF CFD RESULTS FOR 3-D UNSTRUCTURED MESHES

Robert W. Neely  
Lockheed

RTOP 505-63-50

**Research Objective:** Computational Fluid Dynamics (CFD) methods are used routinely to predict spatial and temporal distributions of flowfield velocity components, density and total energy per unit volume. From these primitive variables, a number of other important properties are computed, such as surface pressure coefficient, local Mach number, and flowfield static pressure. The objective of this research was the development of needed graphical software for use in displaying and analyzing the large variety of numerical results obtained from 3-D CFD solution procedures based on unstructured computational-grid topologies.

**Approach:** The graphical display of 3-D CFD results obtained from unstructured grids required the development of fast and efficient data search algorithms, coupled with a suitable graphics workstation on which to run the software and display the computed results. The approach taken was to develop the needed software using a robust plotting language together with graphics software capabilities available with the SG 4D series of graphics workstations.

**Accomplishment Description:** A complete 3-D plotting code was developed to display data generated from a CFD code using unstructured grids. The plotting code permits the display of the computational grid used in the calculation, together with Mach number contours, pressure contours, velocity vectors and particle traces. Figure 27(b) shows sample results displayed for a typical CFD calculation including the symmetry plane grid distribution, body-surface flow-variable contours, outer flow-field variable contours, and outer flow-field particle traces. Using the hardware features inherent in the SG 4D series of graphics workstation, the analyst can translate and/or magnify the display as desired.

**Significance:** The graphics program developed permits the rapid selection and plotting of CFD-generated three-dimensional flowfield data, thus enabling the aerodynamicist to better understand steady and unsteady fluid dynamic phenomena under investigation.

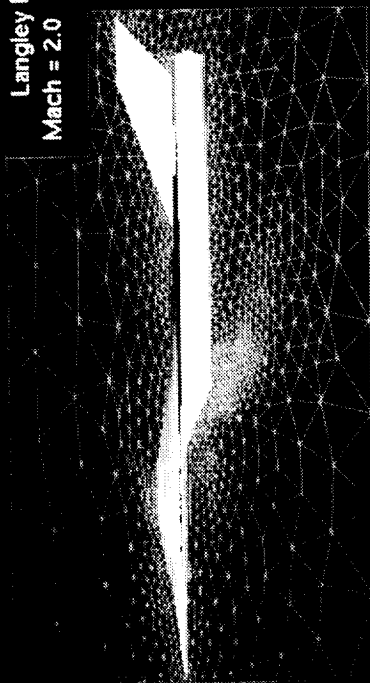
**Future Plans:** To further refine the graphics capability for 3-D CFD codes using unstructured computational meshes by adding additional flow-variable displaying options.

Figure 27 (a).

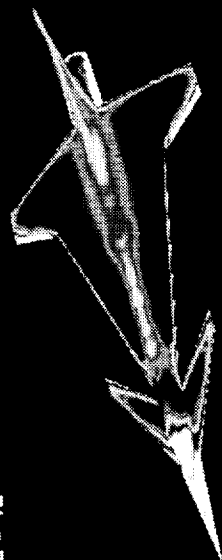


Computer Graphics Code Developed for Unstructured-Grid  
CFD Flow Solvers

Langley Fighter  
Mach = 2.0 Alpha = 12°



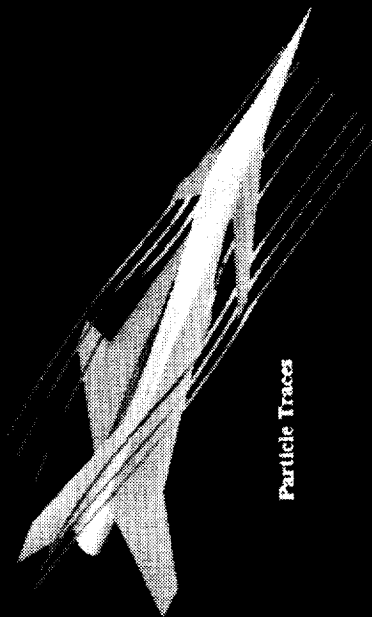
Symmetry Plane



Coefficient of Pressure Contours



Coefficient of Pressure Contours



Particle Traces

Figure 27 (b).

# LIQUID CRYSTALS USED FOR FLOW VISUALIZATION IN TDT BENCHMARK MODEL TESTS

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Lockheed Engineering and Science Company

Robert M. Bennett and David A. Seidel  
Unsteady Aerodynamics Branch

and  
José A. Rivera, Bryan E. Dansberry, Moses G. Farmer and Clinton V. Eckstrom  
Configuration Aeroelasticity Branch

RTOP 505-63-50

**Research Objective:** Two of the objectives of the Benchmark Models Program include obtaining data useful for the evaluation of CFD codes and the understanding of the physics of unsteady flows. Determining the locations of shock waves, boundary layer transition, and separated flow regions over a wing are needed to meet these objectives. The application of liquid crystals to the surface of the model has been investigated for visualization of these flow phenomena.

**Approach:** Shear sensitive liquid crystals have been developed for transition detection and to a lesser extent for separated flow visualization in both flight and wind tunnel tests. These liquid crystals have been used for two of the benchmark model tests in the Langley Transonic Dynamics Tunnel (TDT). The liquid crystals are sprayed on the wing and the resulting color patterns are observed using TV cameras mounted in the slots of the test section floor and ceiling. The existing wind tunnel lighting was used.

**Accomplishment Description:** The liquid crystals have been used during steady flow tests on the rigidized NACA 0012 model mounted on the pitch and plunge apparatus (PAPA) in July 1990. The results gave an indication that the boundary layer transition strip was working. For many conditions, shock locations were visible on the surface of the model. For moderate angles of attack at transonic Mach numbers, complex three dimensional separation patterns were apparent. The left portion of figure 28(b) shows an indication of the location of the foot of the shock as the light colored line on the surface. The liquid crystals were also used during the test of the flexible wing with an 18% circular arc airfoil section. The observed patterns shown in the right portion of the figure indicate a complex flow near the tip of the wing and a shock wave at a nearly constant chord location inboard.

**Significance:** Visualization of shock and separation patterns are invaluable for understanding the overall flow over a wing. For example, it gives insight for selecting the appropriate CFD code for application. The method is simple, inexpensive, and in many cases can be used on a non-interference basis.

**Future Plans:** Further application will be made to the NACA 0012/PAPA test is scheduled for January 1991. The observed flow patterns will help in interpreting the pressure measurements. The results will be used in the benchmark model presentations and reports.

Figure 28 (a).

# LIQUID CRYSTALS USED FOR FLOW VISUALIZATION FOR BENCHMARK MODEL TESTS IN TDT

Wing with NACA 0012 Airfoil



Wing with 18% Circular Arc  
Airfoil

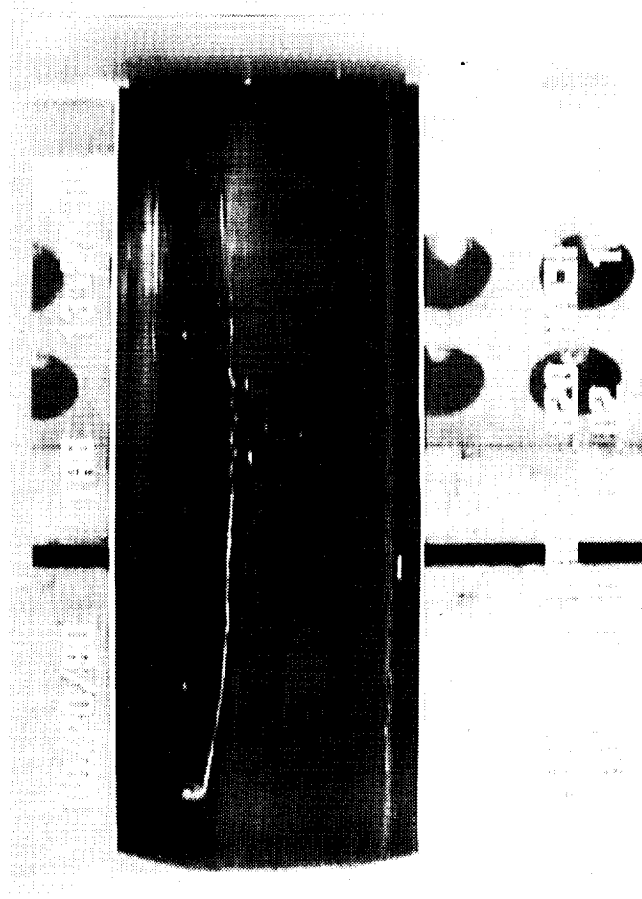


Figure 28 (b).

# TRANSONIC SHOCK-INDUCED DYNAMICS OF A FLEXIBLE WING WITH AN 18% CIRCULAR ARC AIRFOIL DETERMINED IN TDT

Robert M. Bennett and David A. Seidel  
Unsteady Aerodynamics Branch

and

Bryan E. Dansberry, Moses G. Farmer, Clinton V. Eckstrom, and José A. Rivera  
Configuration Aeroelasticity Branch

RTOP 505-63-50

**Research Objective:** Periodic transonic shock boundary oscillations are known to occur over a narrow range of Mach numbers on thick rigid circular-arc airfoils as illustrated in the left half of figure 29(b). The objective of this research was to determine the dynamic response of a flexible wing under these conditions. This model is an element of the SDyD Benchmark Models Program and is an investigation intended to aid in the physical understanding of complex unsteady transonic aerodynamics.

**Approach:** A simple flexible wing was designed and built at LaRC and tested in the Transonic Dynamics Tunnel (TDT) for a quick look at the shock-boundary layer-induced dynamics. The wing was rectangular in planform with an 18 inch chord and 45 inch span. The primary wing structure consisted of a 1/2 inch thick aluminum plate with beveled leading and trailing edges. Balsa wood was glued to the upper and lower surfaces of the plate to form an 18% circular-arc airfoil section. The right half of the figure shows the model mounted in the TDT. It was cantilevered from the wall and a splitter plate was used to offset the root from the wind tunnel wall boundary layer. The model was instrumented with bending and torsion strain gages at the root and accelerometers on the outer portion of the wing. Configurations tested included a variation of stiffness, with and without a transition strip, with and without the splitter plate at the wing root, with three potential fixes, and with the span reduced by 50%.

**Accomplishment Description:** Two wind tunnel tests have been completed, one was a quick look test performed in April 1990, and the other was a longer entry to explore further configurations and test conditions in September 1990. The initial test indicated an increased severity of buffeting of the first bending mode in the Mach range of the shock-boundary layer oscillations. In addition a limit-cycle oscillation appeared at the frequency of a wing "third bending like" mode that involved coupled splitter plate motion. The effects of the configuration variables have been measured on both the buffeting and limit-cycle oscillation. Detailed data reduction is currently underway.

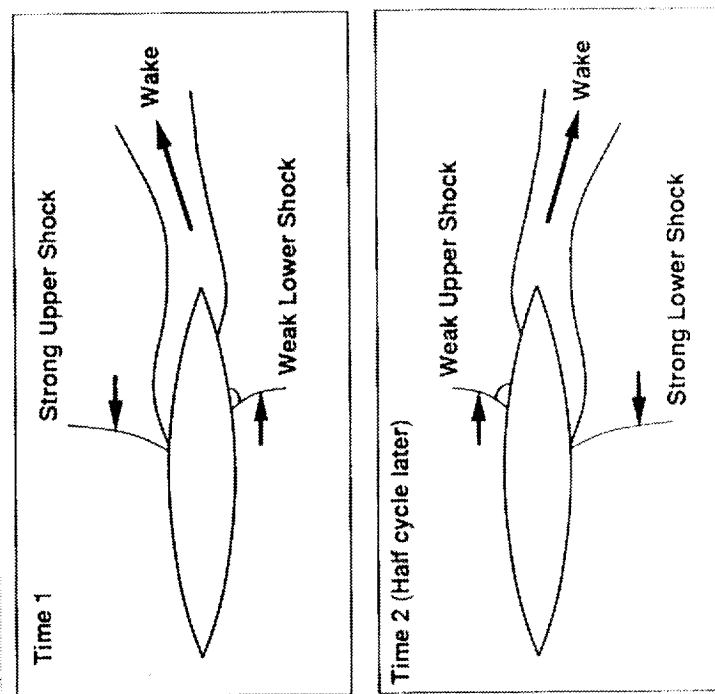
**Significance:** These results will significantly enhance the understanding of the off-design effects of buffeting and transonic separated flows. The limit cycle oscillation encountered may also be similar to those that have plagued fighter aircraft.

**Future Plans:** Data reduction will be continued and the results documented in formal presentations and reports. Building and testing of an additional wing with unsteady pressure instrumentation will be considered after the results of this test are evaluated.

Figure 29 (a).

# FLEXIBLE WING WITH 18% CIRCULAR ARC AIRFOIL TESTED IN TDT

## Sketch of Shock-Boundary Layer Oscillation



## Model Mounted in TDT



Figure 29 (b).

# REYNOLDS NUMBER EFFECTS ON UNSTEADY PRESSURE STUDIED IN 0.3M CRYO TUNNEL

David A. Seidel  
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RTOP 505-63-50

**Research Objective:** This effort had two objectives. The first was to develop and test experimental techniques for measuring unsteady pressures in a cryogenic environment. The second objective was to measure the effects of Reynolds number on the unsteady pressure distribution of an oscillating, two-dimensional, supercritical airfoil with free transition.

**Approach:** The airfoil tested, SC(2)-0714, is a well documented 14 percent thick supercritical airfoil. This two-dimensional airfoil has previously been tested in the 0.3 meter Transonic Cryogenic Tunnel (0.3M TCT) to measure steady surface pressures. A method was developed to install pressure transducers in the model that would withstand repeated cryogenic cycling. An oscillating drive system was developed for the 0.3M TCT that was capable of handling the thermal expansion and contraction experienced by the tunnel test section during operation. The drive system was designed to oscillate a two-dimensional model in pitch. A total of 43 unsteady pressure transducers were installed in the model.

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**Accomplishment Description:** Measurements were made over a range of Reynolds numbers, based on a chord length of 6 inches, from 6 million to 35 million. Mach number was varied at Reynolds numbers,  $R_n$ , of 15 and 30 million. For each data set, static pressure measurements were made from  $-2.5$  to  $2.5$  deg. in  $0.5$  deg. increments. Unsteady pressure measurements were taken at mean angles of attack of from  $-2$  to  $+2$  deg. in  $1$  deg. increments. Frequency was varied from  $5$  Hz to a maximum of  $60$  Hz and amplitude was varied from  $0.25$  deg. to a maximum of  $1$  deg. Unsteady pressure measurements were made at static angles of attack to obtain data which will be used to locate transition. Steady and unsteady pressures were surveyed in the wake and static tunnel floor and wall pressure measurements were made for flow correction calculations. The accompanying figure 30(b) shows the unsteady pressure measured on the airfoil at a Mach number of  $0.720$  at two Reynolds numbers, 6 million and 30 million. The airfoil was at a mean angle of attack of  $0.0^\circ$  and was oscillated in pitch  $\pm 7.5^\circ$  about the mean angle at a frequency of  $15$  Hz. Shown in the upper right corner of the figure is the mean, or average, pressure on the airfoil at the two Reynolds numbers. The higher Reynolds number results in more of the airfoil upper surface experiencing supersonic flow. Shown in the lower half of the figure are the real and imaginary harmonic components of the airfoil pressure on the upper and lower surface at the frequency of oscillation. As shown in the mean pressure, the upper surface unsteady pressure shows a larger supersonic region at 30 million Reynolds number than at 6 million. Very little difference can be seen between the two lower surface unsteady pressures.

**Significance:** A two-dimensional unsteady pressure data set has been obtained for a supercritical airfoil previously tested in the 0.3M TCT. This data set shows the influence of Reynolds number on unsteady pressures and can be used to determine when such effects are important. In addition, this data set can be used for CFD code validation.

**Future Plans:** The data set will be reported in a NASA TM.

Figure 30 (a).

# REYNOLDS NUMBER EFFECTS ON UNSTEADY PRESSURE STUDIED IN 0.3 M CRYO TUNNEL

SC(2)-0714 Airfoil



$M_\infty = .720$   
 $\alpha = 0.0^\circ \pm 0.75^\circ$   
 $f = 15 \text{ Hz}$

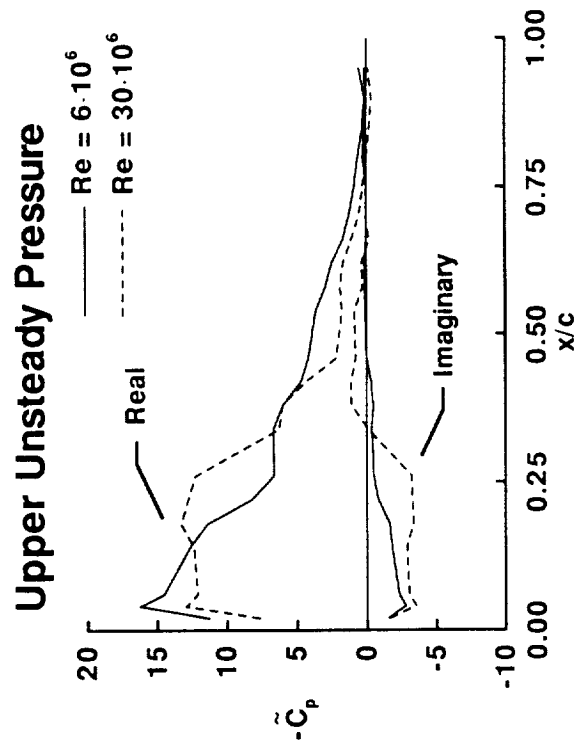
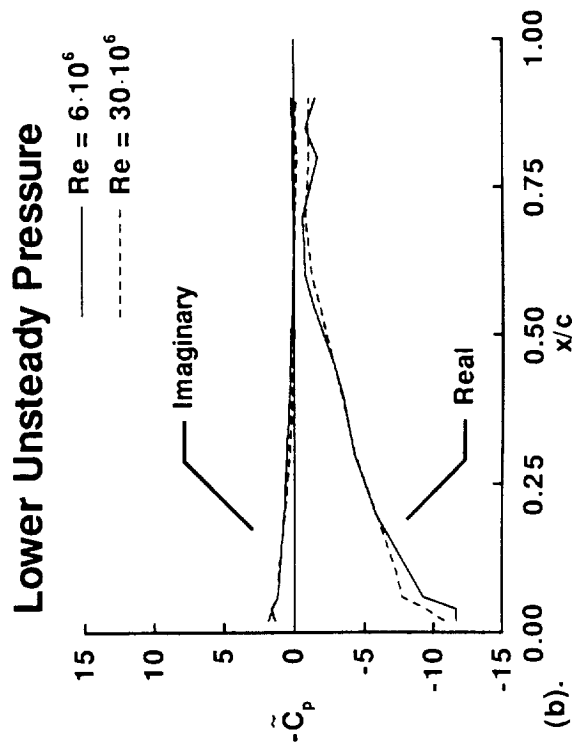
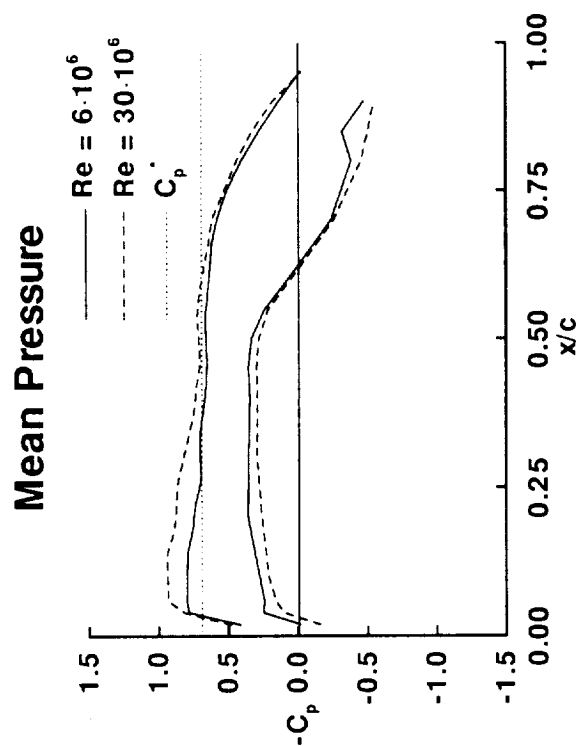


Figure 30 (b).

# AEROSERVOELASTICITY

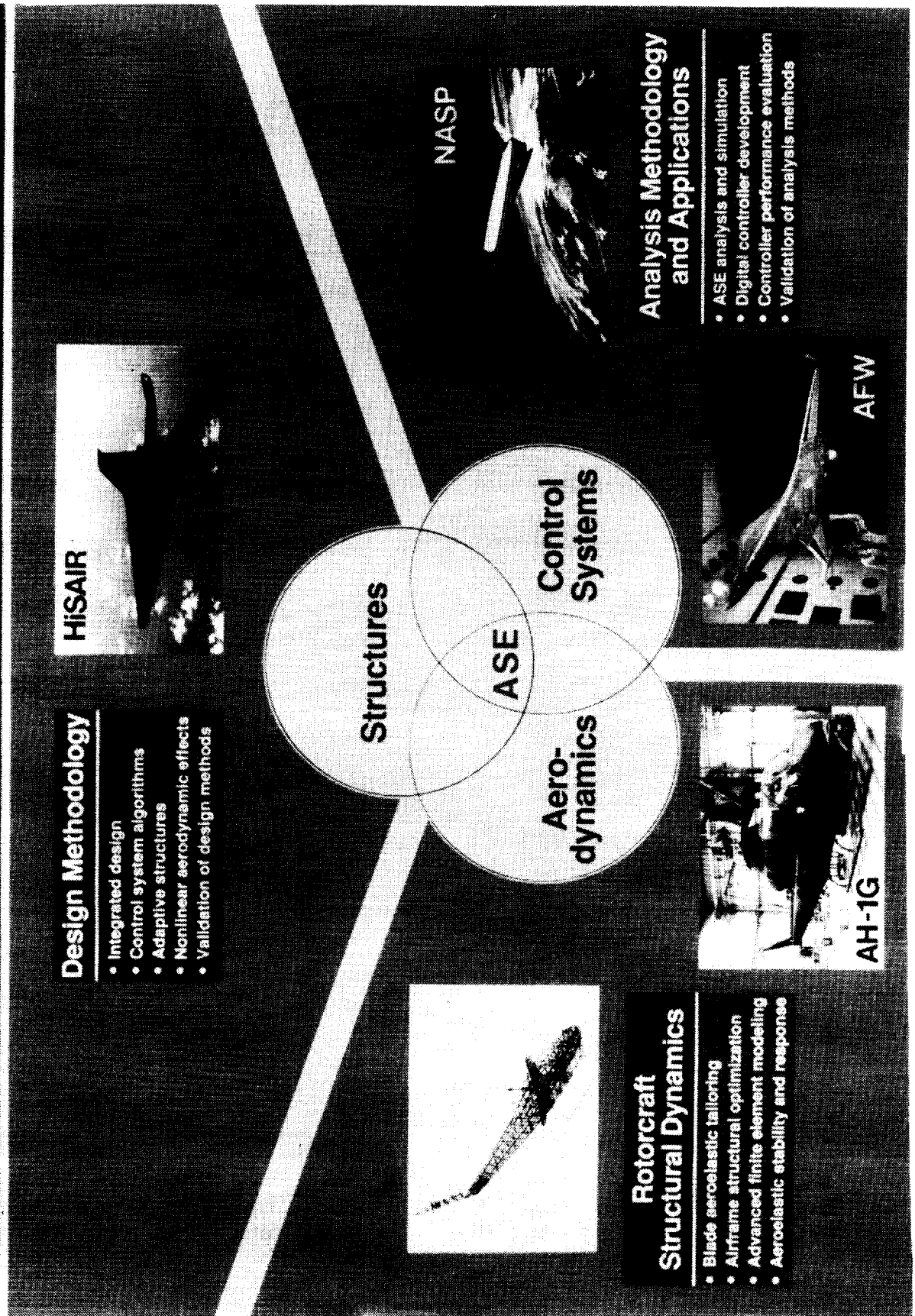


Figure 31 (a).



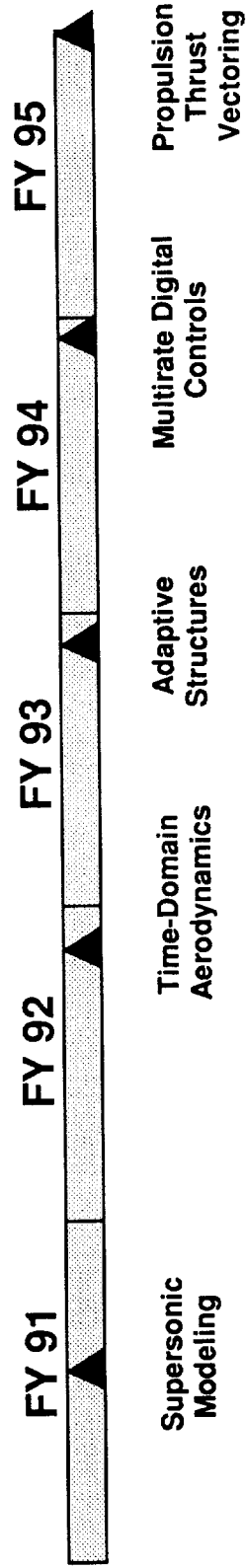
# AEROSERVOELASTICITY FUTURE PLANS (FY 91-95)

GOAL

PREDICTION AND CONTROL OF AEROELASTIC RESPONSE

KEY OBJECTIVES

- MODELING



- NONLINEAR ANALYSIS METHODS

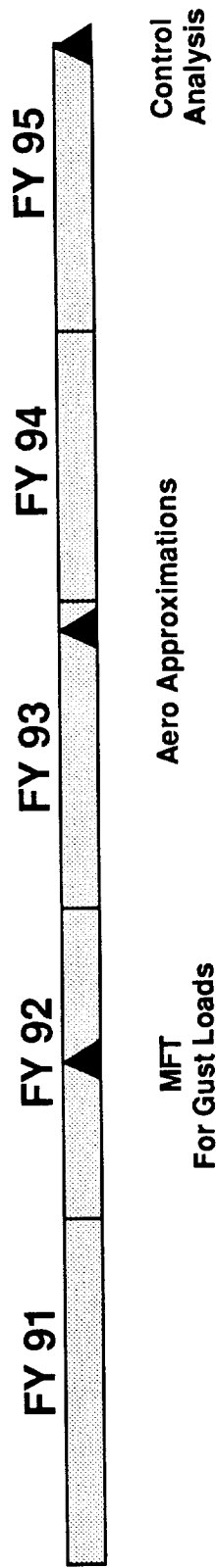


Figure 32 (a).

# AEROSERVOELASTICITY FUTURE PLANS (FY 91-95)

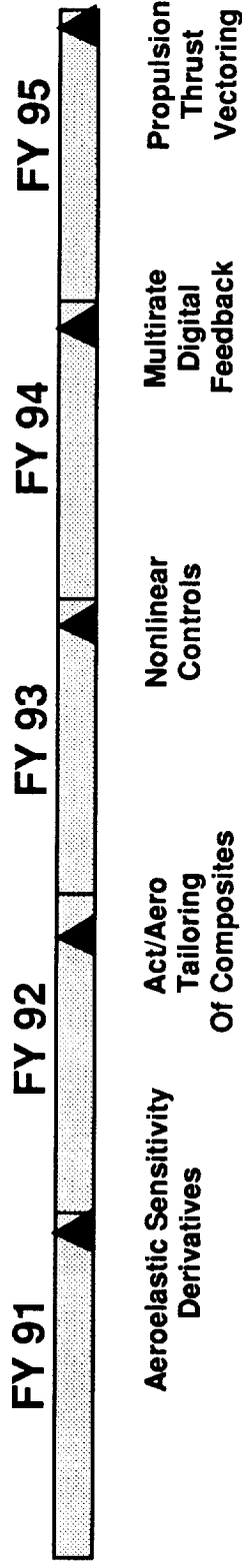
## GOAL

### ADVANCED SYNTHESIS METHODOLOGY

## KEY OBJECTIVES

- INTEGRATED MULTIDISCIPLINARY DESIGN

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- INTEGRATION OF EMERGING TECHNOLOGIES

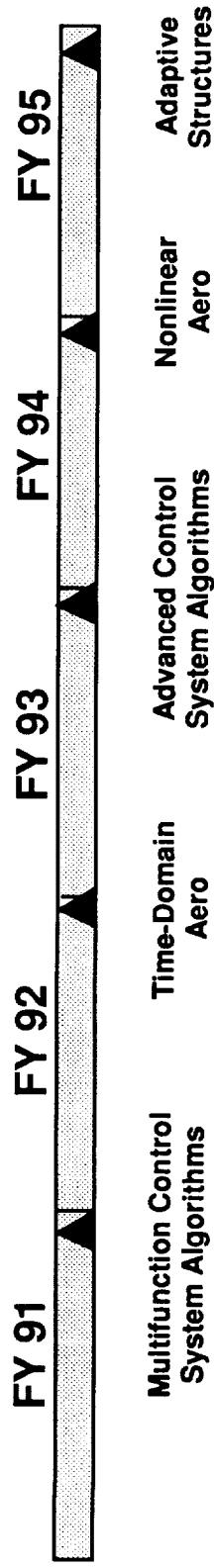


Figure 32 (b).

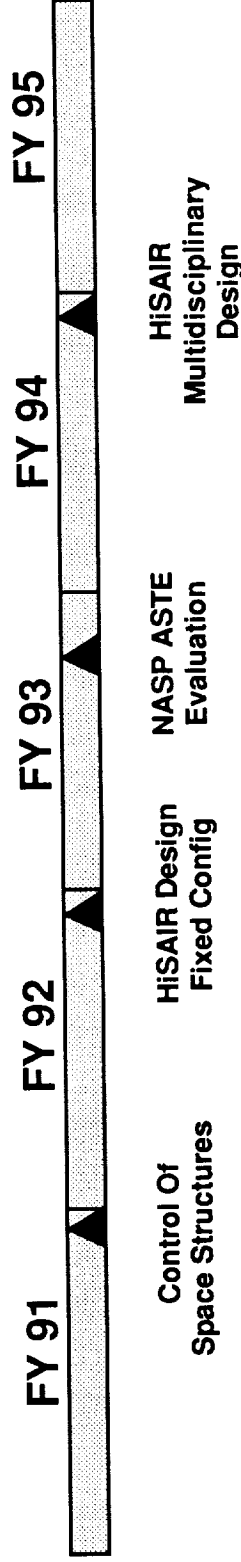
# AEROSERVOELASTICITY FUTURE PLANS (FY 91-95)

## GOAL

APPLY AND VALIDATE METHODOLOGIES

## KEY OBJECTIVES

### ● APPLICATIONS



### ● WIND-TUNNEL EXPERIMENTS

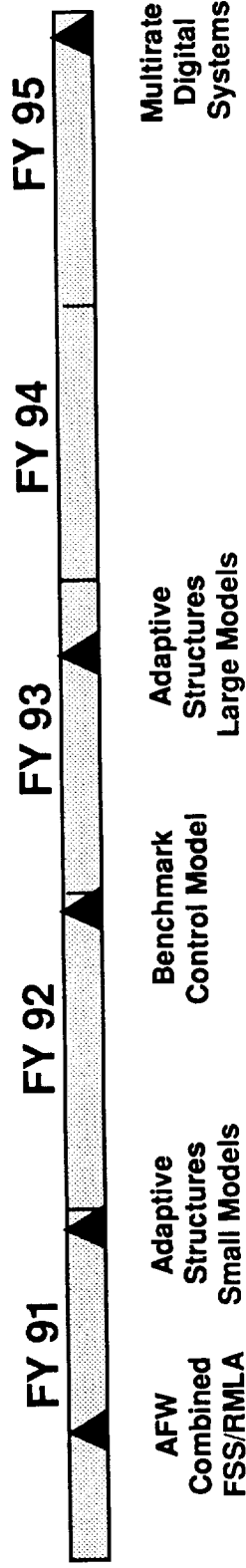


Figure 32 (c).

# AEROSERVOELASTICITY FUTURE PLANS (FY 91-95)

## GOAL

PREDICTION AND CONTROL OF DYNAMIC RESPONSE

## KEY OBJECTIVES

- UNDERSTAND AND IMPROVE STRUCTURAL DYNAMIC CHARACTERISTICS OF ROTORCRAFT

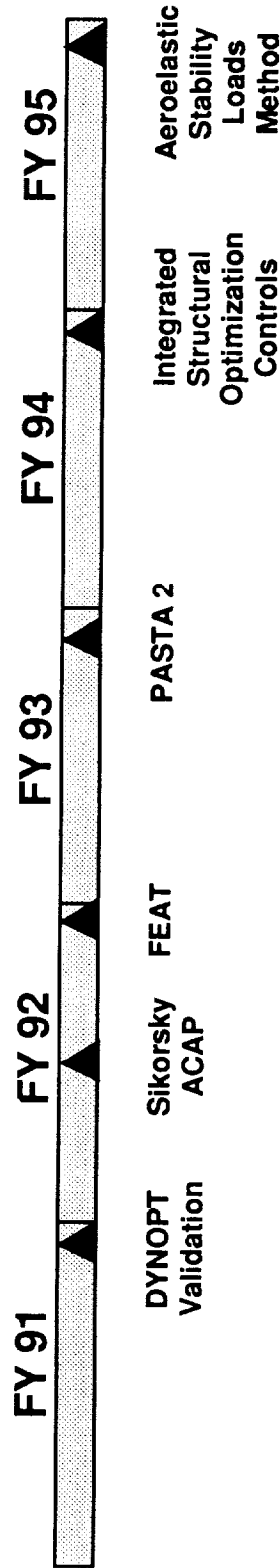


Figure 32 (d).

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# NONLINEAR UNSTEADY AERODYNAMICS IMPROVE PREDICTION OF TRANSONIC AEROELASTIC BEHAVIOR OF THE AFW MODEL

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Jennifer Heeg  
Aeroservoelasticity Branch

Stanley R. Cole

Configuration Aeroelasticity Branch

RTOP 505-63-50

**Research Objective:** Analytical predictions of the aeroelastic behavior of a flexible wind tunnel model are required before flutter testing is initiated. The objective of the present work is to provide the analytical flutter analyses for the Active Flexible Wing (AFW) wind tunnel model (see figure 33(b)) and to compare the results with recent experimental data.

**Approach:** Computational models for the AFW wind tunnel model were developed using doublet lattice unsteady aerodynamic theory for the linear subsonic flutter predictions and the CAP-TSD (Computational Aeroelasticity Program-Transonic Small Disturbance) unsteady aerodynamic code for the transonic nonlinear flutter predictions. For the nonlinear CAP-TSD analyses, the procedure first determines the static aeroelastic shape of the AFW configuration resulting from certain flight (Mach number and dynamic pressure) and model (angle of attack and control surface angles) conditions. Dynamic perturbation analyses are then performed about the deformed shape to obtain the transonic (nonlinear aerodynamics) aeroelastic behavior of the wind tunnel model.

**Accomplishment Description:** A comparison of linear and nonlinear flutter boundary predictions (Mach number versus dynamic pressure) for symmetric motions of the AFW wind tunnel model are shown on the figure. Also shown on the figure are the experimental symmetric results obtained at transonic speeds. Although linear theory adequately predicts the aeroelastic behavior of flutter models at subsonic conditions, the predicted linear boundary tends to remain relatively flat with Mach number and thus fails to capture the very sudden drop in stability observed at the transonic Mach numbers. This is to be expected since linear theory cannot be used to accurately predict transonic aeroelastic behavior because of the presence of nonlinear flow phenomena. The nonlinear aerodynamic or CAP-TSD prediction, however, indicates a potentially dangerous transonic flutter "dip." The discrepancy between the experimental transonic flutter dip defined by the no-flutter track and the CAP-TSD prediction is thought to be due to unmodeled flow phenomena.

**Significance:** This study identified the importance of using nonlinear unsteady aerodynamic codes for predicting the aeroelastic stability of flexible vehicles at transonic flight conditions. The CAP-TSD prediction provided valuable information to guide the wind tunnel test engineers during the flutter testing of the AFW model.

**Future Plans:** Nonlinear flutter analyses for the antisymmetric configuration has been initiated. In addition, further studies are underway to understand the discrepancies involving the transonic flutter "dip." Code and modeling enhancements will be identified to improve the correlation between the analyses and test data at these conditions.

Figure 33 (a).

# NONLINEAR UNSTEADY AERODYNAMICS IMPROVE PREDICTION OF TRANSONIC AEROELASTIC BEHAVIOR OF THE AFW MODEL

- Linear Analyses: Doublet Lattice
- Nonlinear Analyses: CAP-TSD

## ACTIVE FLEXIBLE WING WIND-TUNNEL MODEL

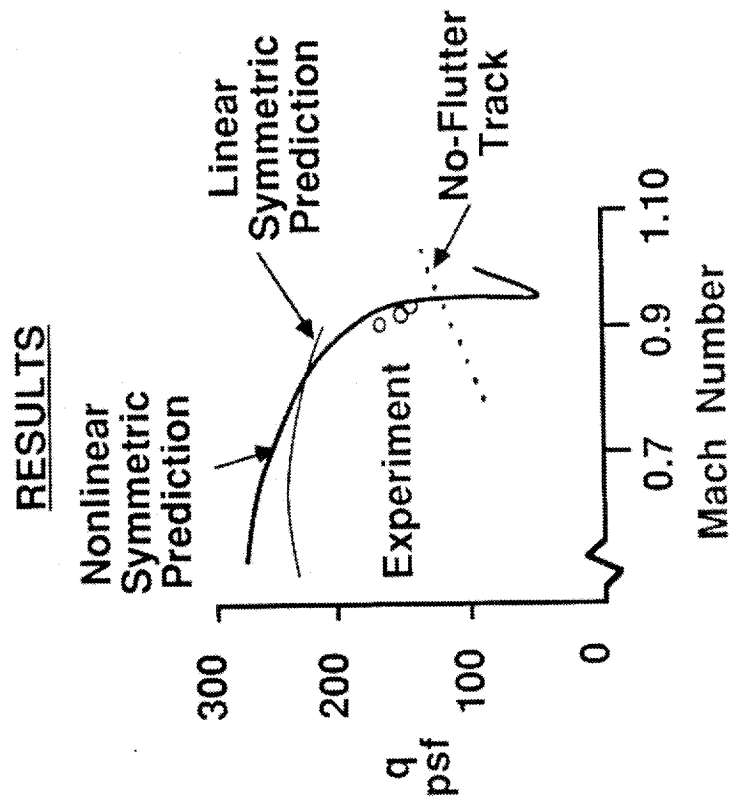
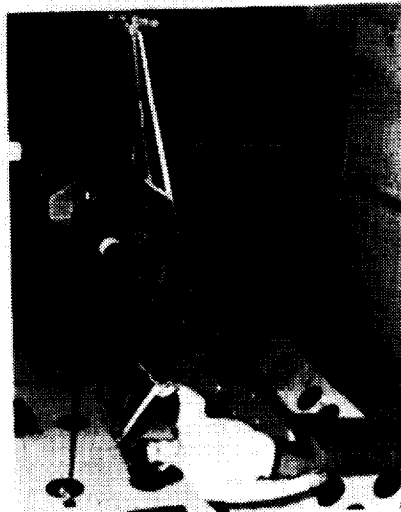


Figure 33 (b).

## FLUTTER CONTROL SUCCESSFULLY DEMONSTRATED IN THE TDT USING THE ACTIVE FLEXIBLE WING WIND TUNNEL MODEL

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Aeroservoelasticity Branch

Stanley R. Cole  
Configuration Aeroelasticity Branch

RTOP 505-63-50

**Research Objective:** The Active Flexible Wing (AFW) Program is a joint NASA-LaRC / Rockwell program with the overall program goal of demonstrating multi-input/multi-output (MIMO), multifunction digital control of a sophisticated aeroelastic wind tunnel model. The research objectives of the program are to validate the analysis, synthesis, simulation, and test methodologies necessary to perform such a demonstration.

**Approach:** In the accompanying figure 34(b), the AFW wind tunnel model is shown mounted in the test section of the NASA-LaRC Transonic Dynamics Tunnel (TDT). The approach taken to accomplish the goal and objectives is to design, implement, and test various MIMO control concepts on the AFW wind tunnel model. Two wind tunnel tests are planned with progressively more complex control-law implementations in each test: during the first test, single-function MIMO control laws were designed and tested separately; during the second test, single-function MIMO control laws will be designed separately but tested simultaneously. Flutter suppression (FS) and rolling maneuver load alleviation (RMLA) are the two control concepts under investigation.

**Accomplishment Description:** The first of the two wind tunnel tests was conducted in the fall of 1989 and four major test highlights are listed in the lower left portion of the figure: (1) the model flutter boundary was determined; (2) the operation of a flutter-stopper device was confirmed; (3) the capabilities of the digital controller were verified; and (4) three different FS concepts were experimentally evaluated. The plots on the right side of the figure together illustrate three of these four accomplishments. The top plot illustrates test highlights (1) and (2). The top plot is a time history of a wing accelerometer measured during open-loop testing at the tunnel conditions indicated in parentheses. At about 3 seconds into the time history, an open-loop flutter condition was encountered, as indicated by the increasing acceleration amplitudes. After about one second of increasing amplitudes, the flutter stopper was activated and the wind tunnel model was returned to a flutter-free condition, as indicated by the decreasing acceleration amplitudes. The bottom plot illustrates test highlight (3). It is a time history of the same wing accelerometer measured during closed-loop testing of one of the FS control laws at a dynamic pressure 9 psf above the open-loop flutter boundary. This FS control law was successful in taking the model to a dynamic pressure 51 psf above the open-loop flutter boundary.

**Significance:** This first wind tunnel test affords the opportunity to validate the analysis, synthesis, simulation, and test methodologies. The knowledge and insight gained from this test, especially where experimental results and analytical predictions differ, are extremely valuable and will be applied to future projects.

**Future Plans:** Data reduction from the first test is currently underway, as is planning for the second test, currently scheduled for the spring of 1991.

Figure 34 (a).

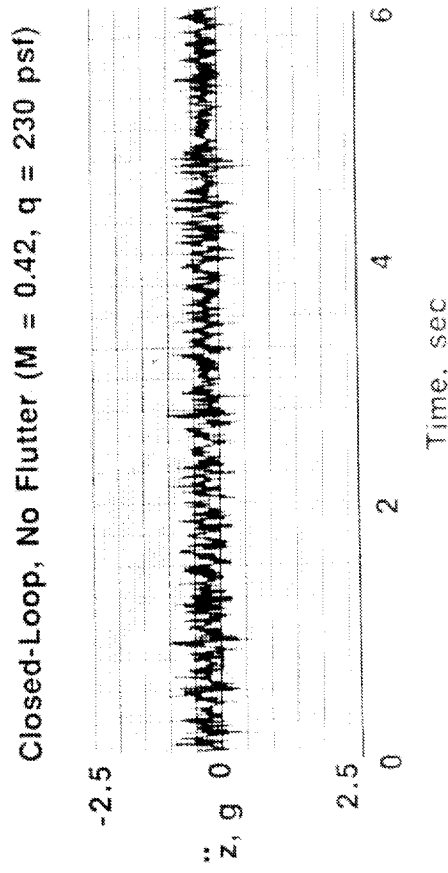
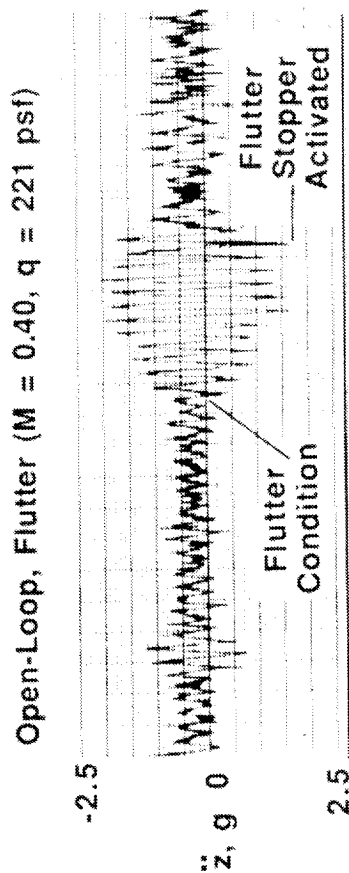


# FLUTTER CONTROL SUCCESSFULLY DEMONSTRATED IN THE TDT USING THE ACTIVE FLEXIBLE WING WIND-TUNNEL MODEL

## AFW Wind-Tunnel Model



## Test Time Histories



## Test Highlights

- Flutter Boundary Determined
- Flutter-Stopper Device Confirmed
- Digital Controller Capabilities Verified
- Three FSS Concepts Evaluated

Figure 34 (b).

# AEROSERVOTHERMOELASTICITY SUCCESSFULLY DEMONSTRATED ON GENERIC HYPERSONIC VEHICLE

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Aeroservoelasticity Branch

Michael G. Gilbert  
Spacecraft Dynamics Branch

RTOP 505-63-50

**Research Objective:** Aerothermal loads are generated on vehicles which undergo atmospheric flight at high supersonic and hypersonic speeds. The objective of this study was to develop the methodology necessary to construct and analyze mathematical models of hypersonic aircraft which include these aerothermal loads and to define the feasibility of applying active controls technology for alleviating any degradation in aeroelastic stability due to thermal loads.

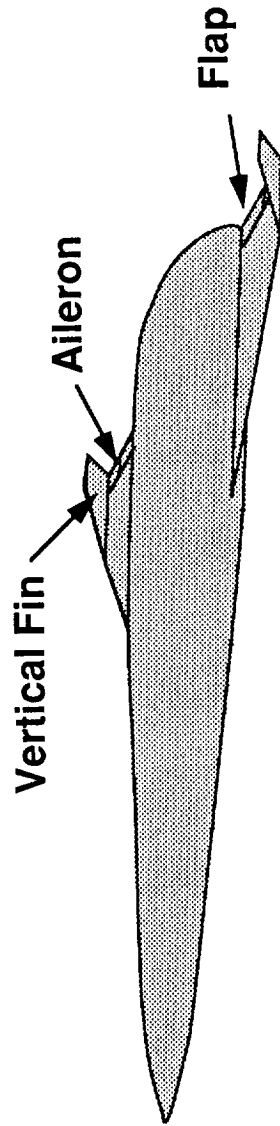
**Approach:** To determine the effects of aerothermal loads on the aeroelastic stability of high-speed aircraft, an aeroservoelastoc procedure that included the use of finite element models, temperature distributions, unsteady aerodynamics, and active controls was developed. The approach first involved applying the temperature distribution predicted for the high-speed flight condition being analyzed to the basic finite element model of the vehicle. The temperature distribution affected the material properties of the structure while the thermal gradients affected internal stresses. Both effects caused a reduction in the stiffness of the vehicle that resulted in lower structural frequencies and only slight changes in mode shapes. Van Dyke's Piston Theory was used to generate the unsteady aerodynamic forces for the vehicle undergoing rigid body, control surface, and elastic deformations. For this study only two supersonic Mach number conditions (Mach 2 and 4) were analyzed; the aerothermal heating that was predicted at Mach 4 was applied at both flight conditions. Since the resulting aeroelastic analyses showed a degradation in the aeroelastic stability of the vehicle, active control concepts were investigated to suppress flutter and to augment the vehicle's ride qualities at the pilot station. Linear Quadratic Gaussian Methods with Loop Transfer Recovery were used to design the flutter suppression system. The ride qualities augmentation system was designed with a pole placement algorithm.

**Accomplishment Description:** The flutter boundary and the ride quality characteristics of the vehicle were significantly degraded when the thermal loads were incorporated into the analysis. The control laws were designed to be robust to the changes expected in the system natural frequencies due to temperature effects. As shown in the lower right diagram, the flutter suppression system raised the flutter boundary of the heated vehicle at Mach 4 to well beyond the flutter boundary of the cold vehicle; at Mach 2, the system completely stabilized the vehicle for all conditions above sea level. A single flutter suppression control law was applied at Mach 2 and Mach 4, indicating its robustness to dynamic pressure and aerodynamic changes. For the ride quality augmentation system, analyses indicated that the system could reduce the root mean square value of the acceleration response at the pilot station by 19.1% for the heated vehicle and by 43.4% for the unheated vehicle. The left sketch provides typical results for the heated Mach 4 case.

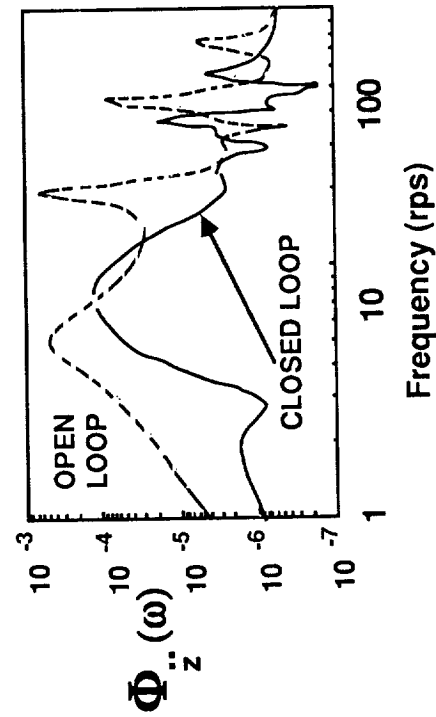
**Significance:** A procedure which includes the influence of thermal loads generated by high-speed aerodynamics has been developed for constructing and analyzing the aeroelastic response characteristics of hypersonic vehicles. This methodology can be applied to any high-speed vehicle where aerodynamic heating is expected and when aeroelasticity is an important design or safety feature.

**Future Plans:** Aeroelastic and aeroservoelastoc analyses from subsonic through hypersonic speeds will be conducted for other hypersonic configurations of interest to NASA and DOD. **Figure 35 (a).**

# AEROSEROVOTHERMOELASTICITY SUCCESSFULLY DEMONSTRATED ON GENERIC HYPERSONIC VEHICLE



## RIDE QUALITY IMPROVEMENT



## FLUTTER SUPPRESSION

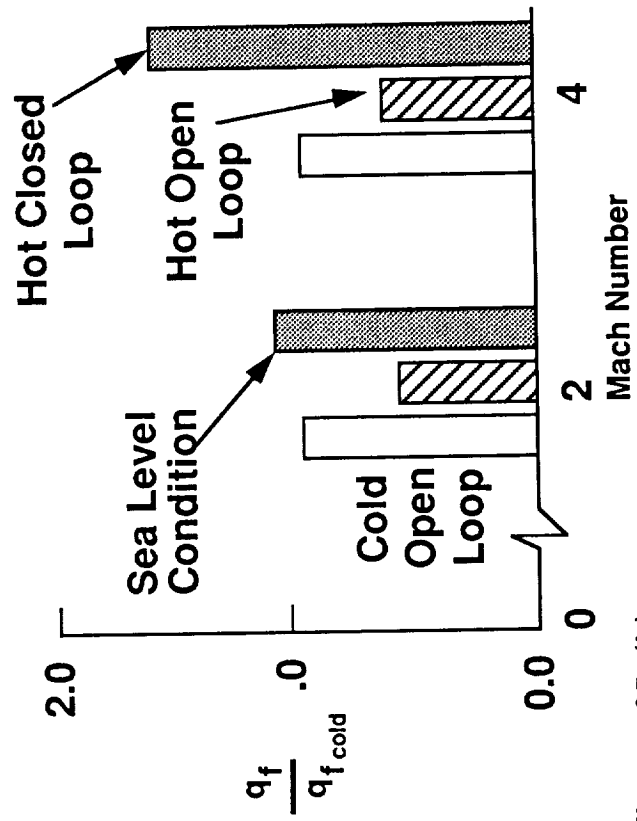


Figure 35 (b).

# OPTIMIZATION SCHEME USED TO OBTAIN MAXIMIZED GUST LOADS FOR NONLINEAR AIRCRAFT

Robert C. Scott, Anthony S. Pototzky (LESC) and Boyd Perry III  
Aeroservoelasticity Branch

RTOP 505-63-50

**Research Objective:** The objective of this activity is to extend the Matched Filter Theory (MFT) Method for obtaining maximized and time-correlated gust loads to aircraft with nonlinear control systems.

**Approach:** The MFT Method offers a means of computing maximized and time-correlated gust loads for linear systems. The methodology has been applied to and successfully demonstrated on a variety of linear aircraft models, some with linear control systems. A constrained optimization scheme has been devised which extends the linear MFT Method so that it can be applied to aircraft configurations requiring nonlinear control systems. The major features of the extended method are illustrated in the accompanying figure 36(b). Beginning in the upper left corner of the figure, linear MFT is used to obtain an initial estimate of an excitation waveform. This waveform is then passed through a coefficient generator which approximates the waveform by Chebyshev polynomials. The coefficients of the Chebyshev polynomials are then used as the design variables in a constrained optimizer. The optimizer varies the coefficients to obtain an excitation waveform that produces maximum loads while maintaining constant waveform energy. The shaded box contains the detailed steps performed during each iteration of the optimization scheme, with accompanying illustrations of quantities that change from iteration to iteration.

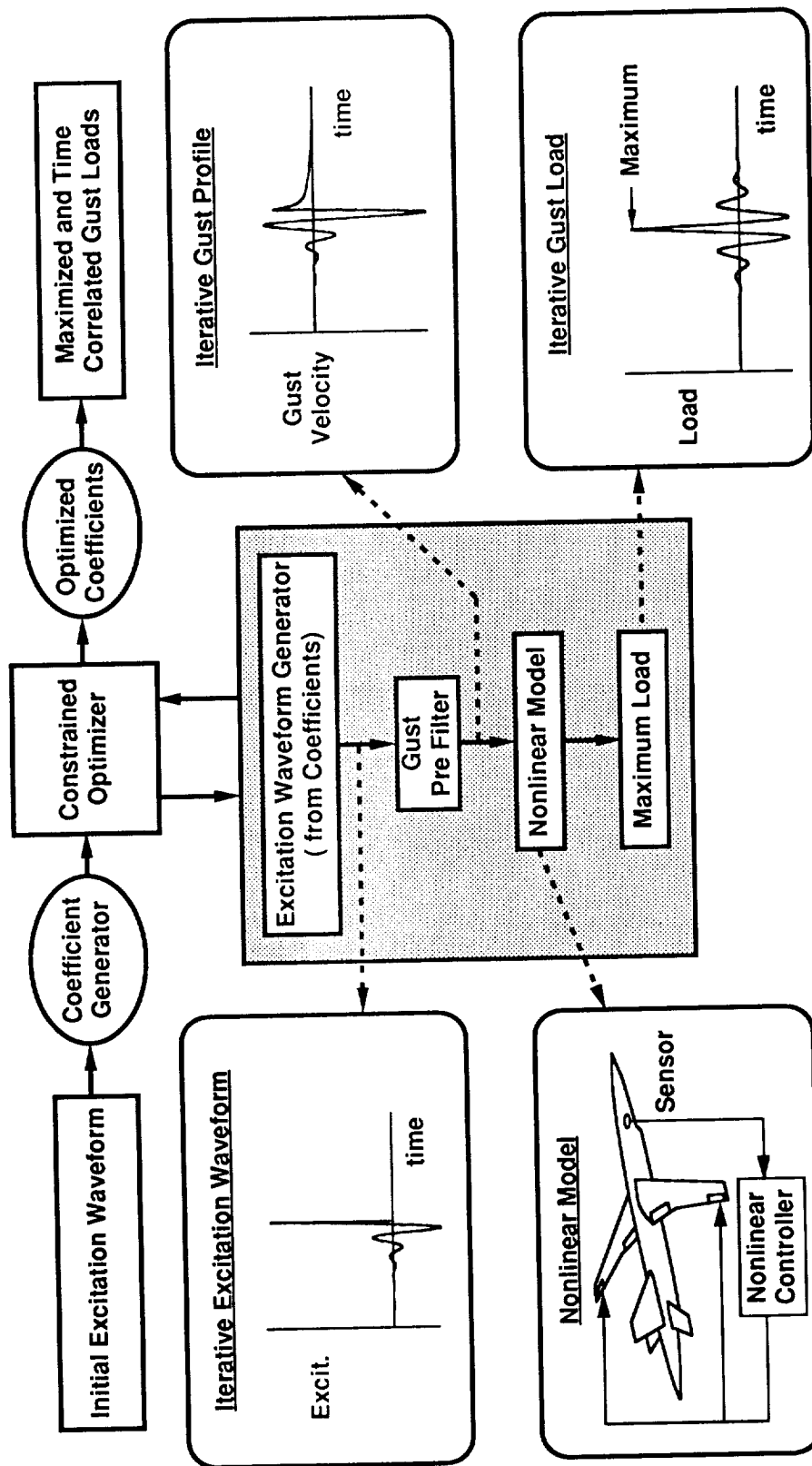
**Accomplishment Description:** The optimization scheme has been applied to both linear and nonlinear aeroservoelastic models of a "rigid" version of the drone aircraft shown in the lower left corner of the figure. The nonlinearities modeled in the control system are limiters on control surface deflections. Application of the scheme to the linear model agreed, as expected, with results obtained from linear MFT and provided confirmation that the scheme was working properly. Application of the scheme to the nonlinear model has shown varied and interesting results: for some types of nonlinearities and loads the optimization scheme provided optimized loads that were within one percent of loads obtained from linear MFT; for other types, the scheme provided loads 5 to 10 percent higher than those obtained from linear MFT.

**Significance:** Modern transport aircraft employ active control systems which almost always contain significant hardware nonlinearities such as actuator rate and deflection limits and deadbands, as well as software nonlinearities. Since most of the established methods used to calculate aircraft gust loads are applicable to linear systems only, the current nonlinear method offers a novel approach to obtain the maximized and time-correlated gust loads for modern transport aircraft.

**Future Plans:** Analyses of more complex systems are planned, including the analysis of a fully-flexible model of the drone aircraft shown in the figure. The results will be presented in April 1991 in Baltimore, MD, at the 1991 Gust Specialist Meeting. An abstract will be submitted to the 1991 AIAA Atmospheric Flight Mechanics Conference to be held in August 1991 in New Orleans, LA.

Figure 36 (a).

# OPTIMIZATION SCHEME USED TO OBTAIN MAXIMIZED GUST LOADS FOR NONLINEAR AIRCRAFT



**Figure 36 (b).**

## DIGITAL CONTROL SYSTEM STABILITY AND ROBUSTNESS DETERMINED ON-LINE DURING WIND TUNNEL TESTING

Anthony S. Pototzky (LESC), Carol D. Wieseman, Sherwood Tiffany Hoadley,  
Vivek Mukhopadhyay, and Boyd Perry III  
Aeroservoelasticity Branch

RTOP 505-63-50

**Research Objective:** The objective of this effort is to develop a Controller Performance Evaluation (CPE) methodology capable of determining real-time the stability and robustness of digital control systems, thereby improving model and wind tunnel safety.

**Approach:** The methodology was derived using multivariable control theory and was implemented using a series of microcomputers. The CPE procedure systematically excites the wind tunnel model at test conditions using the various control surfaces in a symmetric or antisymmetric manner. From the recorded excitations and time responses at the plant and the controller outputs, transfer matrices were digitally computed. Matrix procedures were then used to analytically determine the singular values and determinant loci from the control system return-difference matrices. The results of the matrix procedures were used to directly determine stability and robustness for closed-loop systems or to predict these closed-loop characteristics from responses taken while the control system was open loop.

**Accomplishment Description:** During recent Active Flexible Wing wind tunnel tests, the CPE procedure determined stability and robustness of active flutter suppression systems and other digital control systems, and was very useful in estimating plant and controller transfer matrices for comparisons with predictions. The plot on the left side of figure 37(b) illustrates the "atmospheric line" (combinations of dynamic pressure and Mach number at atmospheric pressure in the Transonic Dynamics Wind Tunnel) along which testing was conducted. The horizontal cross-hatched line represents the open loop flutter dynamic pressure of 230 psf. CPE results are shown on the right side of figure 37(b) for three dynamic pressures: 125 psf, 200 psf, and 250 psf. The CPE results presented are plots of the singular values of the return difference matrix (at the plant input) and plots of the determinant of the same matrix. The plots corresponding to 125 psf were obtained open loop. This information predicts the closed-loop system to be stable and with sufficient robustness (gain and phase margins). The pairs of plots corresponding to 200 psf and 250 psf were obtained closed loop. This information indicates that the closed-loop system is stable, but with increasingly less robustness. The closed-loop system went unstable at 272 psf.

**Significance:** The CPE procedure proved to be a valuable tool; it identified potentially destabilizing controllers before actually closing the loop on a control system, thereby avoiding catastrophic damage to the wind tunnel model or to the wind tunnel itself. The CPE procedure was also valuable in computing open loop controller and plant transfer matrices which were used to check out and improve existing control system designs.

**Future Plans:** The system of CPE codes will be enhanced to improve their capabilities and speed for on-line monitoring of multi-input/multi-output control system stability and robustness. In addition, CPE will be used to evaluate all digital control systems to be tested during the 1991 Active Flexible Wing wind tunnel tests.

Figure 37 (a).

# DIGITAL CONTROL SYSTEM STABILITY AND ROBUSTNESS DETERMINED ON-LINE DURING WIND-TUNNEL TESTING

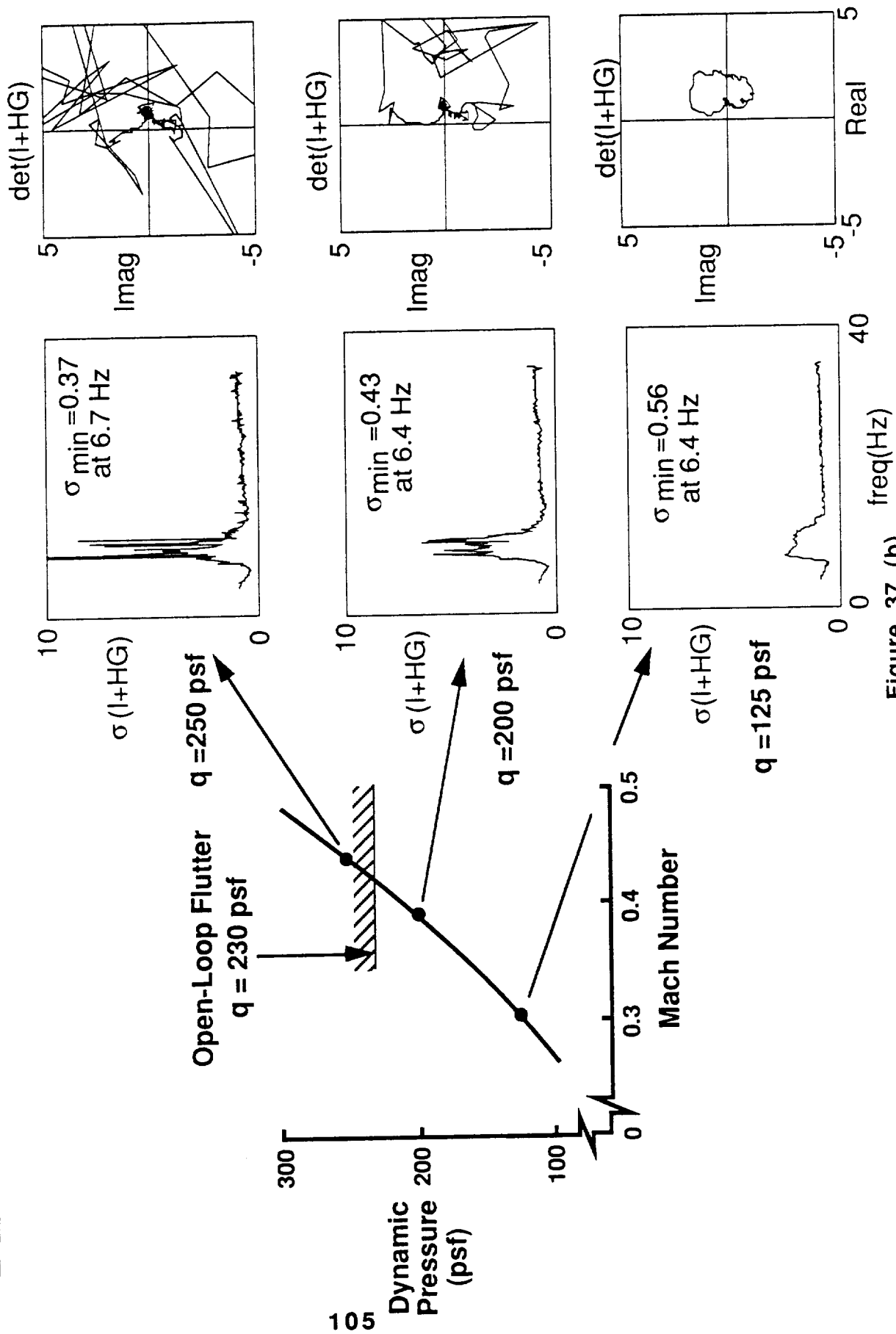


Figure 37 (b).

## HOT BENCH SIMULATION USED TO TEST FUNCTIONALITY OF AFW DIGITAL CONTROLLER

Sherwood T. Hoadley and Sandra M. McGraw (LESC)  
Aeroservoelasticity Branch

RTOP 505-63-50

**Research Objective:** The Active Flexible Wing (AFW) Program is a joint NASA-LaRC / Rockwell International effort with the overall program goal of demonstrating multi-input/multi-out (MIMO), multi-function, digital control of a sophisticated aeroelastic wind tunnel model. The objective of the present activity is to validate the functionality of three different rolling control laws coded on the AFW digital controller.

**Approach:** This validation is performed using a hot bench simulation (HBS), developed specifically for this purpose, and shown in the upper right hand corner of figure 38(b). In the HBS, the AFW digital controller is coupled to the Langley Advanced Real-Time Simulation System (ARTS) via a high speed optical network. ARTS is comprised of Cyber 175 computers (which have been programmed to accurately simulate the aeroelastic characteristics of the AFW wind tunnel model) and Eagle 1000 graphics computers (which provide, in near real time, a visual display of the simulated motion of the model). Simulated closed-loop behavior of the AFW wind tunnel model is obtained by coupling the simulated aeroelastic characteristics (residing on the Cyber 175) with coded control laws (residing on the AFW digital controller). Simulated closed-loop responses from the HBS are compared to corresponding closed-loop responses from other sources (but which use the same aeroelastic characteristics of the wind tunnel model). Agreement between the two pairs of responses confirms that the digital controller has been coded correctly, thereby validating its functionality.

**Accomplishment Description:** All three rolling control laws have been coded on the AFW digital controller and are in various stages of being validated using the HBS. Validation of one of those laws, the roll trim system, is indicated in the figure. On the left side of the figure are photographs of graphical images of the AFW wind tunnel model, taken from the HBS graphics terminal. Using the roll trim system, the model has been commanded to roll from the wings-level position to the wings-vertical position. The plot on the bottom of the figure is a comparison of the roll angle response from the HBS (solid line) and that from a separate analysis (dashed line). Numbers 1, 2, and 3 above the photographs correspond to numbers 1, 2, and 3 on the plot. The agreement is seen to be excellent.

**Significance:** Destruction of wind tunnel models during aeroelastic testing is not an uncommon outcome, especially when control laws are being tested. Careful preparation and precautions are essential to minimize the likelihood of this outcome. Prior to testing, validating the functionality of rolling control laws on the AFW digital controller provides confidence in both the control law and the digital controller, and decreases the likelihood of catastrophe.

**Future Plans:** The rolling control laws will be tested in the late winter of 1991 during the second entry of the AFW wind tunnel model in the Langley Transonic Dynamics Tunnel.

Figure 38 (a).



# HOT BENCH SIMULATION USED TO TEST FUNCTIONALITY OF AFW DIGITAL CONTROLLER

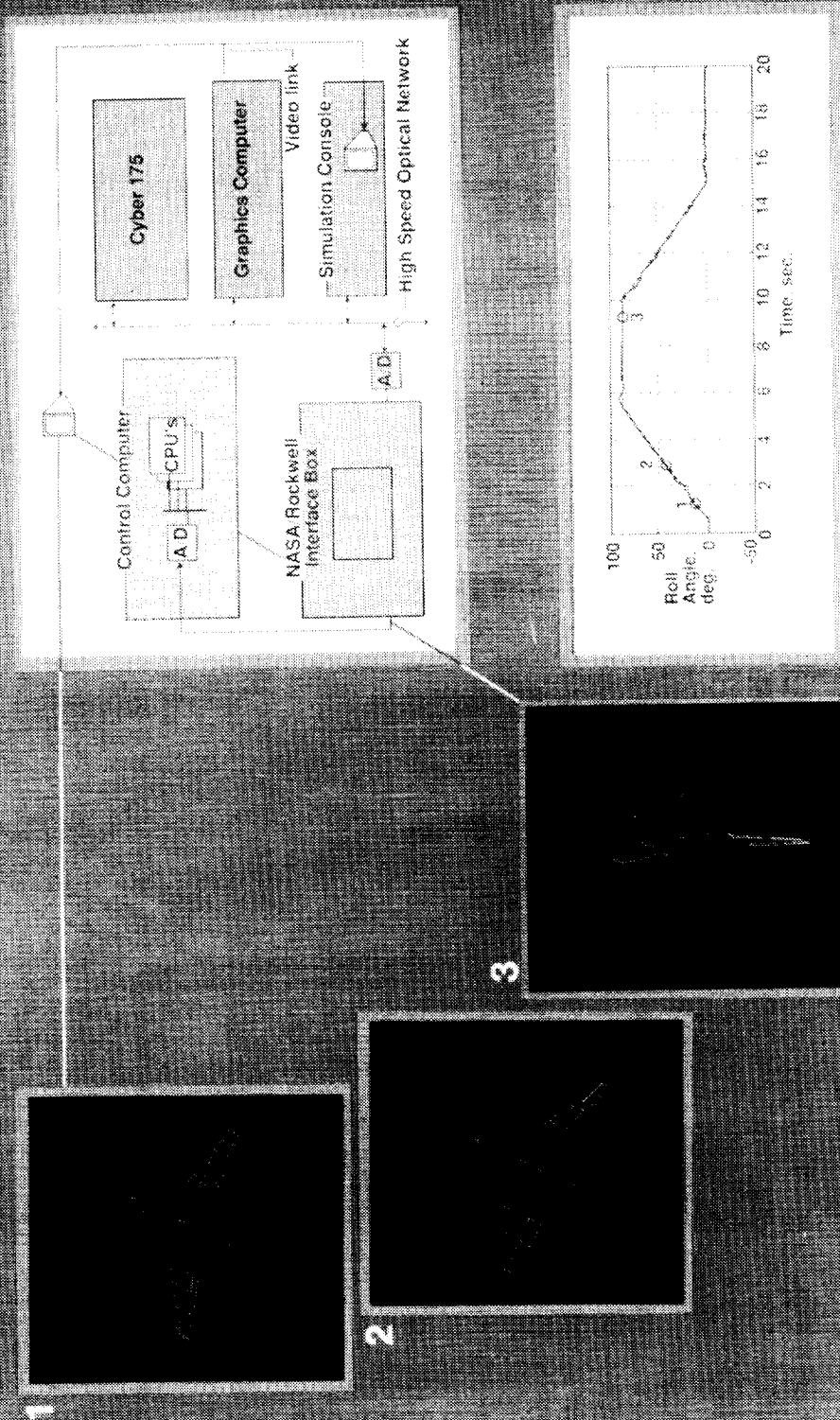


Figure 38 (b).

## TURBULENCE IN THE TRANSONIC DYNAMICS TUNNEL (TDT) MEASURED USING HOT-WIRE/FILM ANEMOMETRY

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Aeroservoelasticity Branch

Donald F. Keller and Maynard C. Sandford  
Configuration Aeroelasticity Branch

RTOP 505-63-50

**Research Objective:** The objective of this research is to measure the three normal components of turbulence at various locations within the test section of the Langley Transonic Dynamics Tunnel (TDT, depicted at the center of figure 39(b)). Power- and cross-spectral density functions of the components of turbulence are the quantities of interest.

**Approach:** Time histories of two of the components (vertical and longitudinal, for example) of tunnel turbulence are obtained by measuring voltages within a small constant-temperature anemometer probe shown at the upper left of the figure. The probe is equipped with two fine hot-film filaments in a cross- or X-configuration and, as shown at the upper right, mounted to a sting in the center of the tunnel. By rotating the anemometer 90° and repeating the test conditions, the same probe is used to obtain the lateral component (and a repeat of the longitudinal component) of tunnel turbulence. After the voltage time histories are obtained at many test conditions, a complex data reduction procedure is performed to obtain, first, time histories of the three normal components of turbulence, and second, power- and cross-spectral density functions of these components.

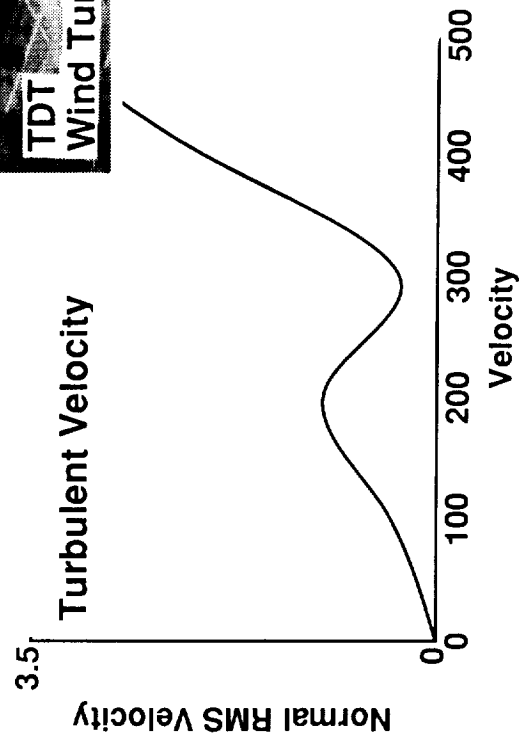
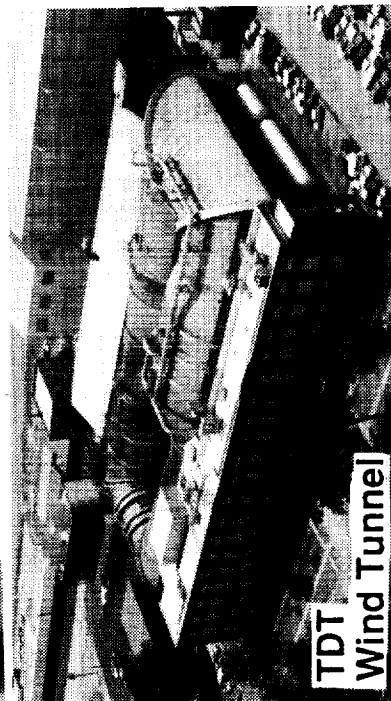
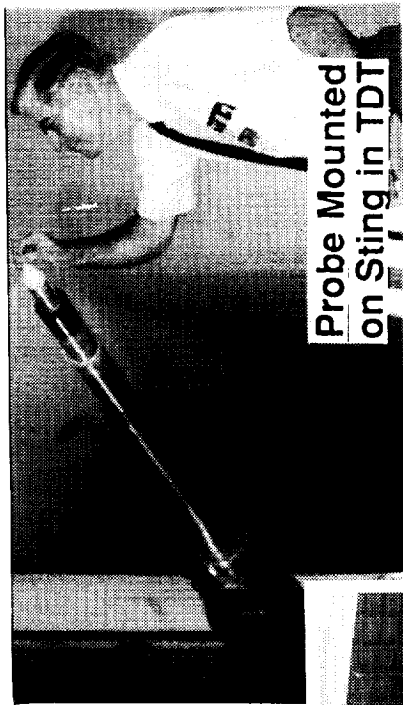
**Accomplishment Description:** Using air at atmospheric pressure as the test medium and using the anemometer described above as the measuring device, data was collected over the complete range of tunnel velocities. The photograph at the upper right shows the anemometer in the center of the TDT test section. Preliminary results are shown in the two plots at the bottom of the figure. The plot on the left shows the root mean square (rms) value of the vertical component of tunnel turbulence as a function of free stream velocity. The rms velocity is shown to increase sharply for tunnel velocities above 300 feet per second. The plots on the right are power spectral density functions of voltage. These PSD functions are proportional to the power spectral density functions of the vertical component of tunnel turbulence at three tunnel velocities shown. The plots suggest a rather uniform power distribution as a function of frequency.

**Significance:** The TDT is a national facility in which many types of dynamic wind tunnel models are tested in varieties of ways by an assortment of "customers." Active controls tests are frequently conducted in the TDT and during the preparation for such tests (specifically, control law design) it is often necessary to have an analytical description of the turbulence in the test section. To date, analytical descriptions of the turbulence in the TDT test section have been educated guesses based on the observations and intuitions of test engineers. This research will take the "guess work" out of this aspect of control law design and will provide, for the first time, an analytical description of the turbulence in the TDT test section.

**Future Plans:** Data reduction is presently underway. Additional wind tunnel testing is planned later next year for the heavy gas test medium.

Figure 39 (a).

# TURBULENCE IN THE TRANSONIC DYNAMICS TUNNEL (TDT) MEASURED USING HOT-WIRE/FILM ANEMOMETRY



Spectra

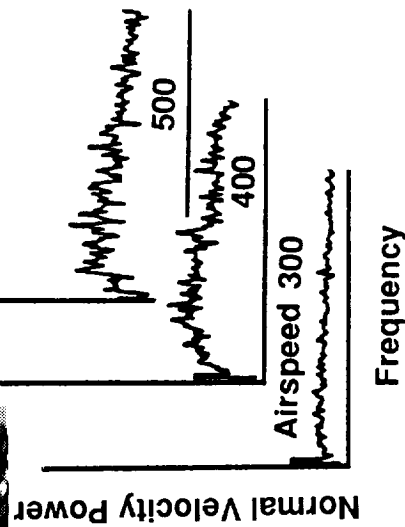


Figure 39 (b).

# SIMULTANEOUS OPTIMAL DESIGN DEMONSTRATED FOR AEROSERVOELASTIC SYSTEMS

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Technion, Israel Institute of Technology

Carol D. Wieseman  
Aeroservoelasticity Branch, SDyD

RTOP 505-63-50

**Research Objective:** The objective of this effort is to develop methods for efficient, multidisciplinary optimization of aeroservoelastic systems that yield, within design constraints and with minimum weight penalty, specified aircraft performance and flutter and control stability margins.

**Approach:** Standard finite-element and state-of-the-art unsteady aerodynamic methods are used to construct a modal data base. Minimum state aerodynamic approximations and dynamic residualization techniques are used to construct a high-accuracy, low-order aeroservoelastic model. Sensitivity derivatives of flutter dynamic pressure, control stability margins, and control effectiveness with respect to structural and control design variables are developed. The roll performance requirement determines equality constraints that affect the sensitivity derivatives. Use of analytical stability derivatives results in an efficient optimization process which allows an increase in the number of design variables when compared with previous methods. The variable to be minimized is a function of the added weight, the flutter dynamic pressure, and the control system gain margins.

**Accomplishment Description:** The modeling technique and the optimization method is demonstrated with an application to a composite wing model with four control surfaces. Required flutter dynamic pressure and roll power are listed at the top of figure 40(b). For this example, the design dynamic pressure is 1.5 pounds per square inch (psi). The structural design variables are the number of  $0^\circ$  and  $\pm 45^\circ$  plies to be added in each of 11 optimization zones over the wing box structure shown at the left of the figure. The control system, diagrammed at the right of the figure, includes roll control for achieving a specified roll performance and flutter suppression for obtaining the required flutter dynamic pressure. Design constraints on the control system requires the gain margins to be  $\pm 6$  db and the phase margins to be  $\pm 60^\circ$ . Typical histories of flutter dynamic pressure ( $q_{\text{flutter}}$ ), change in weight ( $DW_{\text{weight}}$ ), the number of  $\pm 45^\circ$  plies added in the shaded zone at the left of the figure, the flutter suppression system gain ( $K_{fs}$ ), and the roll control system gain ( $K_{rc}$ ) are shown at the bottom of the figure. During optimization, the flutter dynamic is increased from a relatively low value to the performance requirement of 2.16 psi. The number of  $\pm 45^\circ$  plies in the shaded region increases by two, and the weight increases by approximately 0.25 pounds. As a result of the optimization,  $K_{fs}$  increases slightly, and  $K_{rc}$  decreases to less than half of its starting value.

**Significance:** The techniques developed in this effort can be used as an efficient tool in the design of modern aeronautical composite structures and control systems.

**Future Plans:** Future plans include improving the numerical schemes, expanding the scope of objective functions, and applying a new approach that involves use of vibration modes obtained with fictitious masses loading the structure. This new approach also will be applied for efficient time-domain simulation of aeroservoelastic systems where significant structural changes occur during flutter.

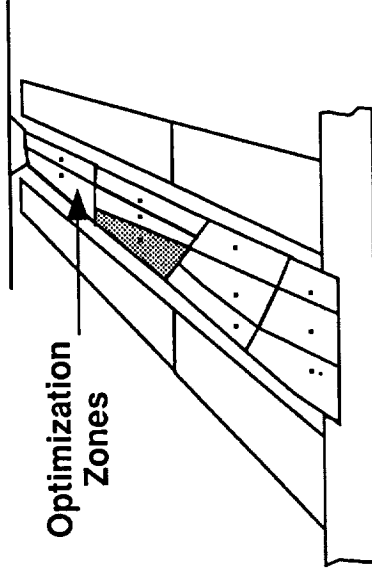
Figure 40 (a).

# SIMULTANEOUS OPTIMAL DESIGN METHOD DEMONSTRATED FOR AEROSERVOELASTIC SYSTEMS

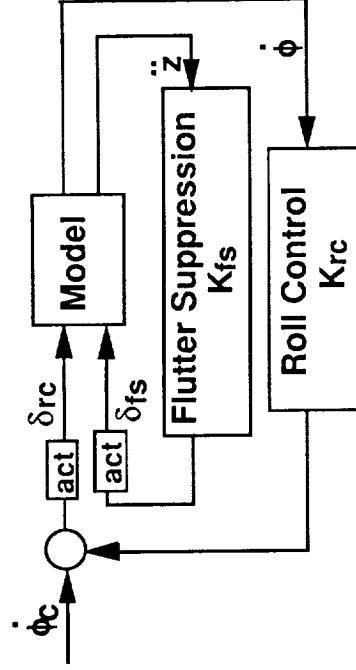
## PERFORMANCE REQUIREMENTS

- $q_{\text{flutter}} \geq 1.44 * q_{\text{design}}$
- Roll power = 3000 in-lb per rad/sec

## STRUCTURES



## CONTROLS



## OPTIMIZATION RESULTS

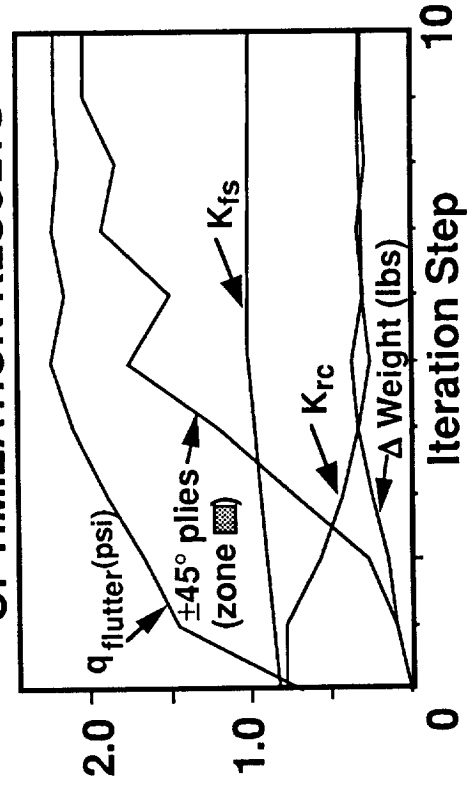


Figure 40 (b).

# DIGITAL CONTROLLER USING REAL-TIME UNIX OPERATING SYSTEM SUCCESSFULLY DAMPS STRUCTURAL RESPONSE

H. J. Dunn  
Aeroservoelasticity Branch

RTOP 505-63-50

**Research Objective:** The objective of this study is to develop the methodology and procedures for applying  $H_\infty$  and  $m$  synthesis techniques in the design of control laws for alleviating structural vibrations associated with large space structures or undesirable aeroelastic response of flexible flight vehicles. In the near term, the suppression of vibratory response is the goal of the control law designs. Systems and results based on  $H_\infty$  and  $m$  synthesis techniques will be compared with conventional LQR/LQG control law designs/results using a large space structure model.

**Approach:** In order to examine the different control laws, a 10-bay truss beam was constructed and is being used as the test object. The 10-bay truss has eight sensors; three accelerometers at the tip ( $x/L = 1$ ), a rate gyro ( $\dot{x}/L = 0.7$ ), and four strain gages at the cantilevered root ( $x/L = 0$ ). The 10-bay truss is controlled by two air jets at the tip of the beam. An Intel 80386 based microcomputer using the Lynx Real-Time Operating System (LynxOS) is being used to implement the control laws and to perform data acquisition.

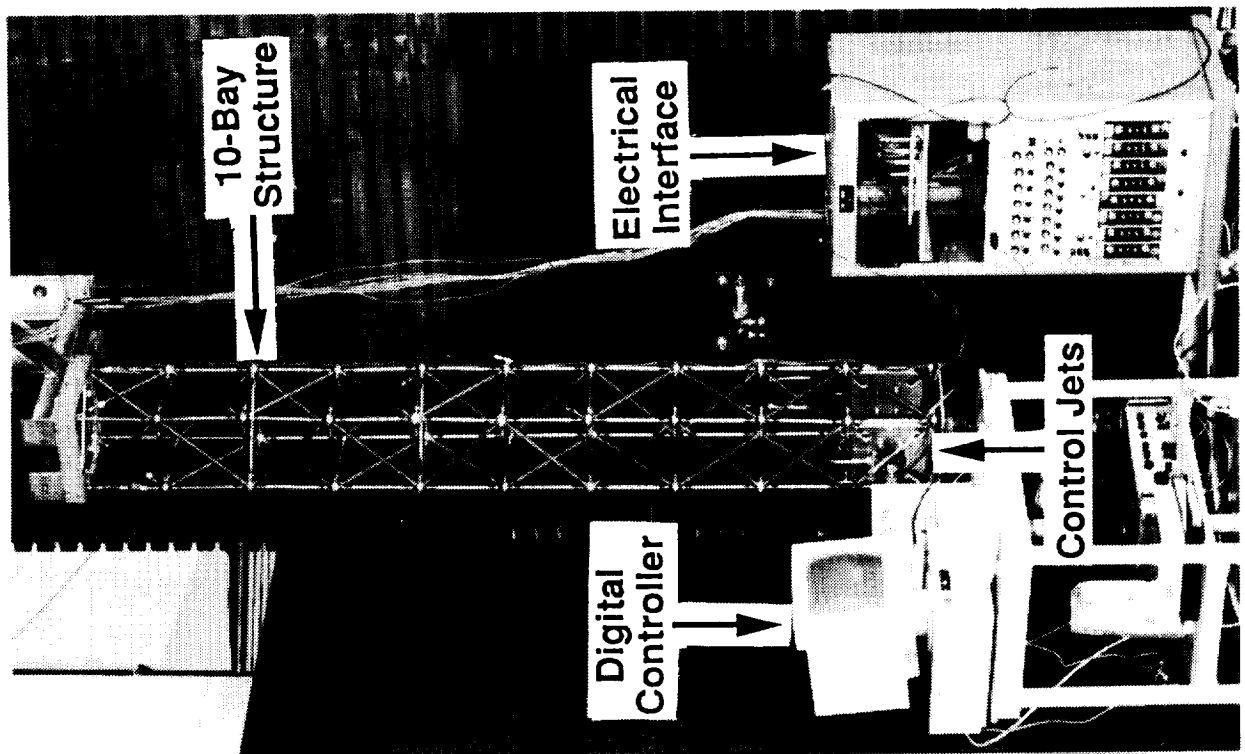
**Accomplishment Description:** An experimental system identification procedure was used to identify a simple second-order system (1 mode) associated with the first-bending mode of the beam. This second-order system was used as the design model for the LQR/LQG design synthesis. A simple generic control law of the form  $(x_k+1 = Ax_k + Bu_k; r_{k+1} = Cx_k + Du_k)$  was developed for the design and implemented on the computer. With the proper electrical interface between the digital controller and the beam, the controller can run an 8th-order control law at a rate of 200 Hz. The figures to the right show an open-loop impulse response of one of the accelerometers and the response with LQR/LQG control law operating. The increase in structural damping as a result of closing the loop was significant.

**Significance:** The comparison of LQR/LQG,  $H_\infty$ , and  $m$  synthesis control law designs will improve the understanding of these new robust control law design techniques. In addition, this project is the first to use a real-time Unix Operating System for the control of dynamic response. In-house design and experimental capabilities will be significantly improved as a result of this investigation.

**Future Plans:** Further experiments have shown that a two-mode design model is required to properly design control laws for this 10-bay truss beam. The two-mode design model will be identified, and the LQR/LQG controller will be redesigned/adjusted with the new design modes.  $H_\infty$  and  $m$  control laws will also be synthesized with the two-mode design model and tested. In addition, hardware modifications will be made to improve the performance of the system. A new data acquisition will be installed that will improve the data acquisition maximum rate and dynamic range from 72 dB to 96 dB. With the addition of a different disk subsystem from the current configuration, the 80386 CPU speed can be increased by a factor of 2.5.

Figure 41 (a).

# DIGITAL CONTROLLER USING REAL-TIME UNIX OPERATING SYSTEM SUCCESSFULLY DAMPS STRUCTURAL RESPONSE



## TEST-RESULTS

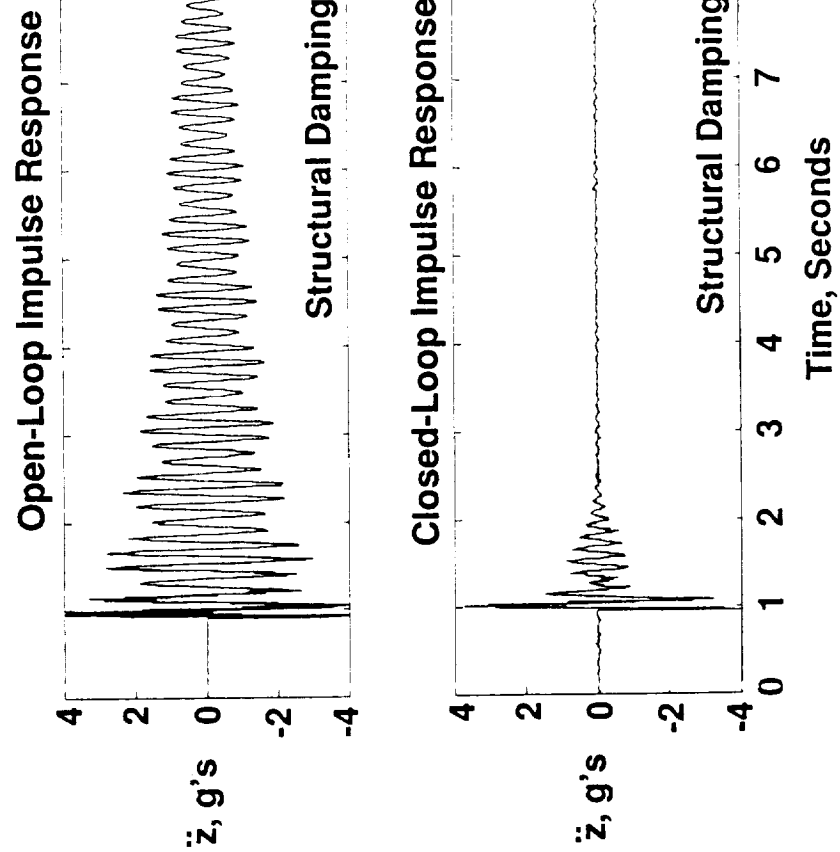


Figure 41 (b).

## FEASIBILITY OF USING ADAPTIVE MATERIALS TO ALLEVIATE AEROELASTIC INSTABILITIES ESTABLISHED

Robert C. Scott  
Aeroservoelasticity Branch

RTOP 505-63-50

**Research Objective:** The objective of this research is to examine the feasibility of using adaptive materials (piezoelectric materials and shape memory alloys) for alleviating undesirable aeroelastic instabilities. Both active and passive applications of adaptive materials were considered and evaluated. This discussion considers the passive application of the shape memory alloy, nitinol, to panel flutter.

**Approach:** For shape memory alloys, the adaptive process (geometry and stiffness changes) due to heating is a relatively slow phenomenon; therefore, these materials were only considered for passive (on/off) aeroelastic control schemes. The chart briefly describes an application of nitinol to the supersonic panel flutter problem. For this application, the nitinol is strained at room temperature to some level up to 8% of its length (the material yield limit). In this deformed condition, the material is embedded within the host material of the panel. At temperatures greater than about 190° a significant change in material properties occurs and the material attempts to return to an undeformed condition. For this application, the four edges of the panel are restrained in plane thus preventing the panel from deforming at the elevated temperatures. The resulting tensile stresses and the change in material properties both have a positive effect on the panels stiffness, through the positive differential stiffness and the increased Young's modulus.

**Accomplishment Description:** Panel flutter is a serious design consideration for all large supersonic flight vehicles. At high supersonic flight conditions where aerodynamic heating becomes a concern, most materials have a tendency to expand further aggravating the panel flutter mechanism or causing the panel to buckle. Analyses have indicated that nitinol can be used to significantly increase the flutter speed of panels (lower right figure 42(b)). This improvement in flutter speed is attributed to the increase in the panel differential stiffness which causes the frequencies of the two critical elastic modes to further separate thereby delaying modal coupling. Since nitinol must be heated to be "activated," this heating can be accomplished through resistive heating of embedded nitinol fibers or through ambient heating of the entire panel.

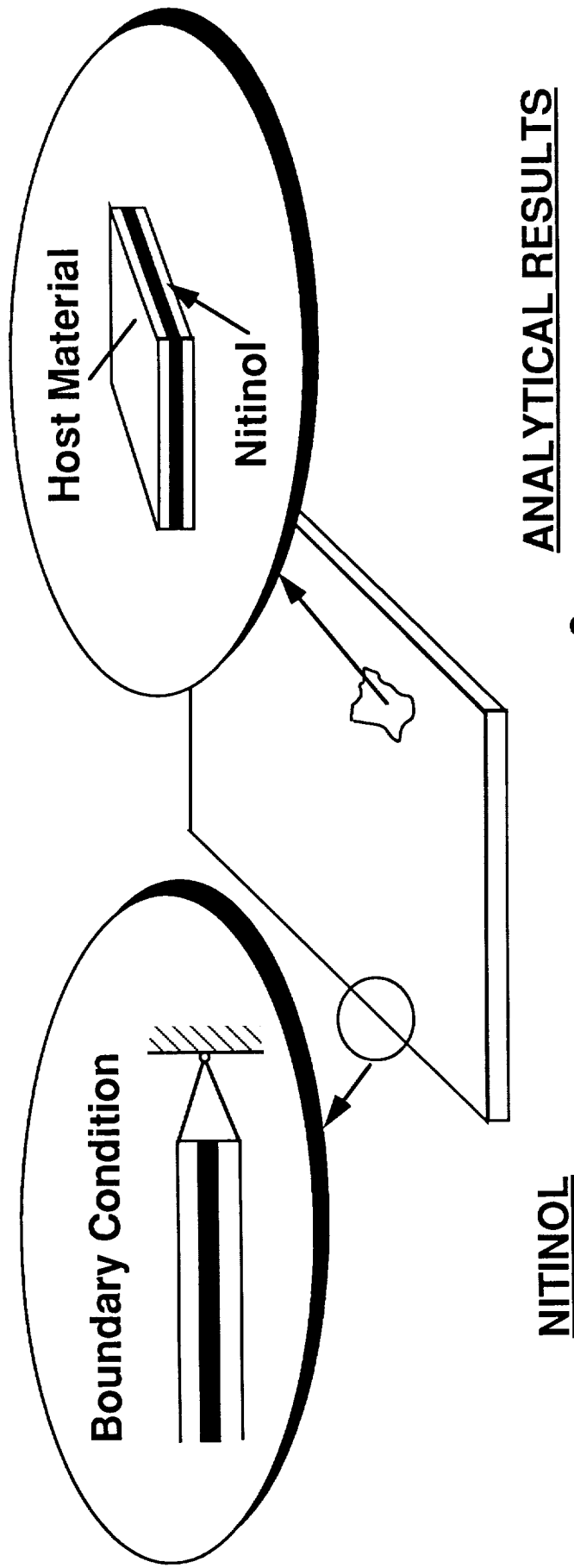
**Significance:** Research has been accomplished to examine the use of adaptive materials for controlling undesirable vibration in large space structures. This is the first investigation where adaptive materials have been examined for controlling dynamic aeroelastic instabilities such as flutter. Various material types have been identified which show promise for aeroelastic applications. Following more detailed studies and tests this application of adaptive materials may be added as an option to be considered by the aircraft designer as he strives to obtain a minimum weight, flutter free vehicle.

**Future Plans:** A paper describing the results of this investigation will be prepared and presented at the 32nd AIAA Structures, Structural Dynamics, and Materials Conference during April 1991. Analyses and wind tunnel test investigations using small, simple models to study both passive and active control applications of adaptive materials will continue.

Figure 42 (a).



# FEASIBILITY OF USING ADAPTIVE MATERIALS TO ALLEVIATE AEROELASTIC INSTABILITIES ESTABLISHED



## ANALYTICAL RESULTS

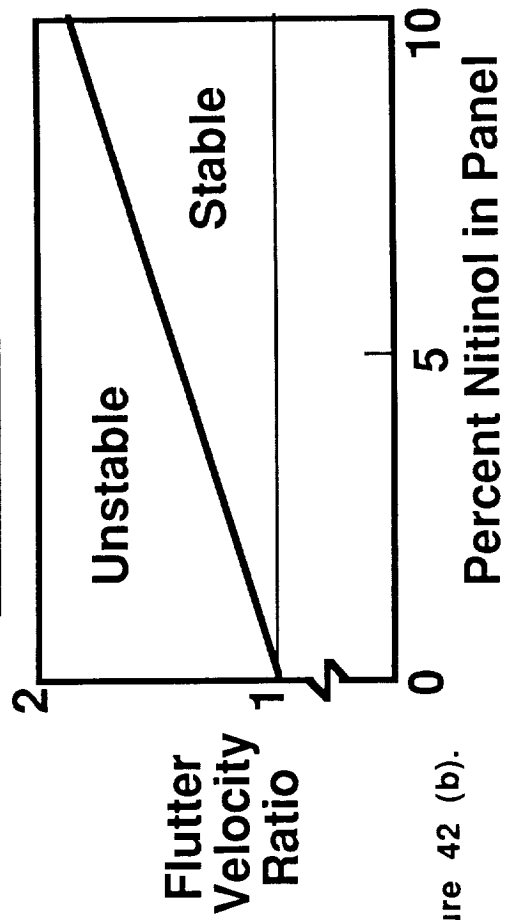


Figure 42 (b).

- Material deformed Up to 8% at Room Temperature
- At Temperatures Above 190°
  - Modulus Increases by Factor of 3
  - Material Adapts to Unstrained Condition

# DIGITAL FEEDBACK SYSTEMS FOR ACTIVE CONTROL OF AIRCRAFT WING LOADS DURING ROLL MANEUVERS

Jessica A. Woods and Anthony S. Pototzky (LESC)  
Aeroservoelasticity Branch

RTOP 505-63-50

**Research Objective:** The objective of this research is to develop active control laws which will reduce bending and torsion moments acting on the Active Flexible Wing (AFW) aeroelastic model during subcritical roll maneuvers.

**Approach:** The reduction of moments is achieved by using a digital feedback control system to optimize combinations of control surface deflections during high-performance roll maneuvers. To simplify design and implementation of the control laws, the control-law structure of the Rolling and Maneuver Load Alleviation (RMLA) system is chosen to be of the gain-feedback type with a low-pass filter in each of the feedback loops. The addition of these low-pass filters reduces the effects of the flexible modes. The basic control law design is defined by roll-rate feedback to two trailing-edge control surface pairs and by load feedback to a leading-edge control surface pair. The associated closed-loop system gains are determined by extensive optimization in which the objective is to reduce a specific peak load to some value below its open-loop value for a given roll maneuver. The existence of a pendulum effect, or an artificial restoring moment, is the only deviation in this methodology from RMLA control systems to be developed for real aircraft.

**Accomplishment Description:** A set of candidate control laws has been developed which, analytically, have been shown to reduce specific peak loads on the AFW model during roll by as much as 50 %. The plot at the bottom left of figure 43(b) indicates that, given the proper input command, nearly the same roll angle performance can be achieved in the open-loop and closed-loop modes. The figure at the bottom right shows that, with the same roll performance, the wing torsion moment can be reduced (by 12.5 %) with a feedback control system.

**Significance:** This methodology is being developed to allow use of digital control systems as a means of reducing aircraft wing loads during roll maneuvers.

**Future Plans:** The control law concepts will be verified during a 1991 wind tunnel test of the AFW model. Procedures to demonstrate viability of this control design on real aircraft are being studied.

Figure 43 (a).

# DIGITAL FEEDBACK SYSTEMS FOR ACTIVE CONTROL OF AIRCRAFT WING LOADS DURING ROLL MANEUVERS

## ANALYSIS METHODS

- System Parameters Optimized to Reduce Loads and Maintain Performance
- Stability Robustness of MIMO Controller Evaluated Using Singular Values

## CONTROL OBJECTIVES

- Reduce Loads to Below Open-Loop Values

## ACTIVE CONTROL DEFINITION

- Roll Rate Feedback to Trailing Edge Surfaces
- Maintain Open-Loop Roll Performance
- Load Sensor Feedback to Leading Edge Outboard Surfaces

## PRELIMINARY RESULTS

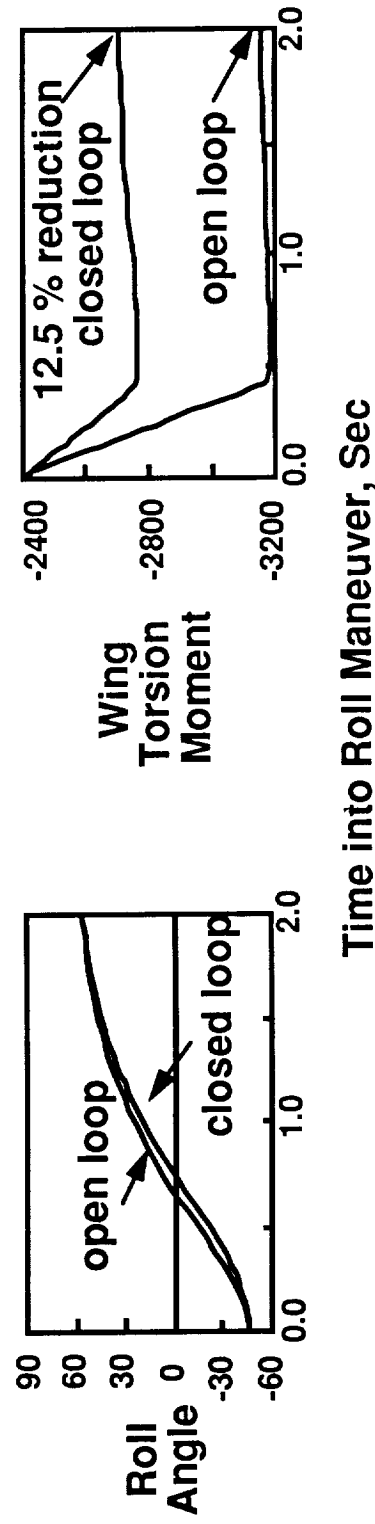


Figure 43 (b).

## ACTIVE STATIC AEROELASTIC CONTROL USING ADAPTIVE MATERIALS

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Purdue University

Jessica A. Woods  
Aeroservoelasticity Branch

RTOP 505-63-50

**Research Objective:** The objective of this research is to investigate enhancement of aircraft maneuverability through the integration of adaptive materials into aeroservoelastic design.

**Approach:** The use of piezoelectric materials that lengthen or shorten in response to an applied electrical voltage as a method of damping the vibration of large flexible space structures has been well-researched. These materials have not been extensively investigated as a means of controlling the deformation of lifting surfaces for atmospheric flight vehicles. Piezoelectrics can be used as replacements for mechanical controls in small missiles or as enhancements to controls for larger aircraft. Early investigations at Purdue University have focused on the development of design parameters to identify the efficiency and practicality of such uses and on the development of multi disciplinary optimization procedures to determine the optimal blending of controls, structures, and piezoelectric materials to enhance aircraft maneuverability.

**Accomplishment Description:** Research has focused on the development of parameters, containing combinations of classical structural stiffness parameters and piezoelectric parameters, that reveal the applicability of this concept. The ability to control lift effectiveness and wing divergence through control laws that specify voltages to be applied in response to lifting surface strains has been demonstrated analytically. Using adaptive materials, wing divergence dynamic pressure ( $q_d$ ) has been shown to increase to over twice the divergence dynamic pressure of a non-adaptive wing before reaching actuator saturation limits. The negative voltage feedback gain,  $K_p$ , between sensor and actuator causes the piezoelectric material to "stiffen" the wing by introducing strain. Since divergence is characterized by the loss of wing stiffness with respect to applied loads, the additional "stiffness" delays the onset of divergence. Considering divergence as an increase in surface lift effectiveness, the divergence boundary occurs when the surface becomes so effective at generating lift that structural load limits are exceeded. The results of this study indicate that negative voltage feedback gains decrease surface effectiveness, thus relieving loads and delaying the onset of divergence. Positive voltage feedback gain reduces  $q_d$ .

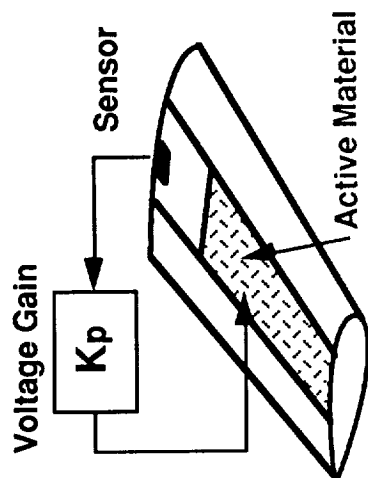
**Significance:** An advanced materials technology has been applied to aeroservoelastic design, and improved static stability has been demonstrated.

**Future Plans:** An optimization procedure to create effective, workable combinations of adaptive materials and advanced composites is being developed. A wind tunnel test to check the validity of these results is being planned.

Figure 44 (a).

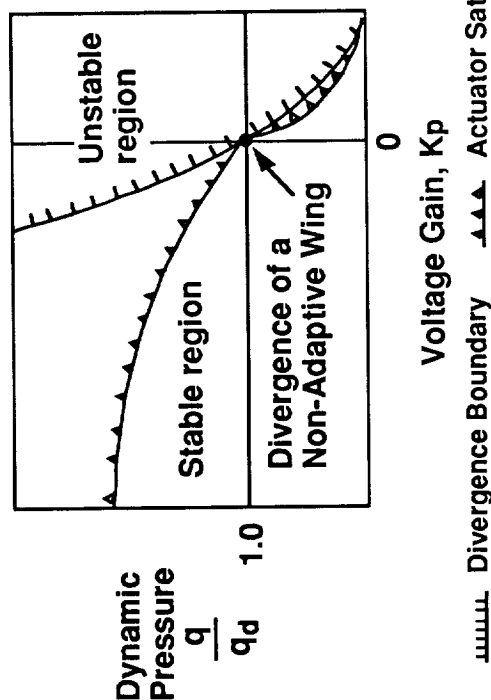
# ACTIVE STATIC AEROELASTIC CONTROL USING ADAPTIVE MATERIALS

## CONTROLLED AIRCRAFT WING



- Piezoelectric materials generate strains under applied electric fields.
- Feedback system senses wing root loads and applies a constant electric field to the piezoceramic material actuator.
- Actuation causes change in wing stiffness and static aeroelastic characteristics.

## DIVERGENCE



## LIFT EFFECTIVENESS

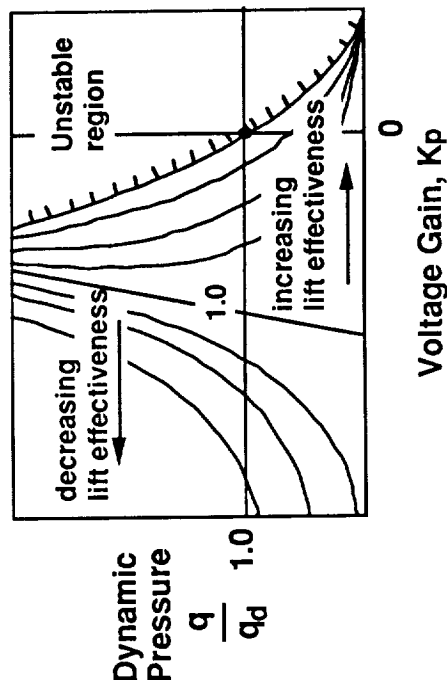


Figure 44 (b).

## PREDICTED DYNAMIC CHARACTERISTICS VALIDATED FOR WARPING-PRONE EXTENSION-TWIST-COUPLED COMPOSITE TUBES

Renee C. Lake  
Aeroservoelasticity Branch

RTOP 505-63-36

**Objective:** The use of composite materials in helicopter structural components is becoming increasingly popular because of advantages in strength-to-structural weight ratio and tailorability. Currently receiving considerable attention is the use of composite materials for designing helicopter rotor blades in which structural coupling associated with the ply layup angles is employed to enhance the dynamic and aerodynamic characteristics. To fully realize the benefits of finite-element analysis codes which include a composite analysis capability, modeling methods and guidelines need to be established such that reliable and accurate solutions may be consistently obtained. The objective of this research is to develop a basic finite-element modeling methodology for composite rotor blades.

**Approach:** This in-house research study is being conducted using the following approach: (1) establish basic finite-element modeling criteria for performing structural dynamic analysis of extension-twist-coupled composite rotor blades through the development and analysis of finite-element models of structurally-coupled composite tubes; (2) conduct ground vibration tests of fabricated composite tubes to establish a structural dynamics experimental data base for structurally-coupled composite designs; (3) correlate analytical and experimental results to verify accuracy of modeling methodology; and (4) apply modeling methodology to rotor blade structures and conduct similar analyses and comparisons with experimental data.

**Accomplishment Description:** Finite-element models of graphite-epoxy composite tubes exhibiting extension-twist structural coupling were formulated for a set of composite warping-prone tubes. The set was comprised of multiple tubes for each of three cross-sectional types, all of which were non-circular in design and were therefore subject to warping deformations. These designs included square, D-shape, and "flattened" ellipse cross-sectional geometries. An MSC/NASTRAN finite-element model of the tube type incorporating the "flattened" elliptical cross section design is shown in the accompanying figure. There were 370 grid points and 350 flat plate elements in the finite-element models for this cross section type. Results from a normal modes analysis of the "flattened" elliptical-type tubes were compared with those obtained experimentally in free-free ground vibration tests conducted for each tube. Five global modes were identified for each tube in the 0-2000 Hz range. The maximum error between test and analysis frequencies was approximately 10%.

**Significance:** This work represents the completion of an intermediate phase in the development of a finite-element modeling methodology for composite rotor blades and demonstrates that the structural dynamic characteristics of composite structures employing extension-twist coupling can be determined analytically within practical engineering accuracy.

**Future Plans:** The results of this research will be documented in a formal NASA/Army report. Furthermore, this methodology will be applied to conventional rotorcraft blades and tiltrotors.

Figure 45 (a).

# PREDICTED DYNAMIC CHARACTERISTICS VALIDATED FOR WARPING-PRONE EXTENSION-TWIST-COUPLED COMPOSITE TUBES

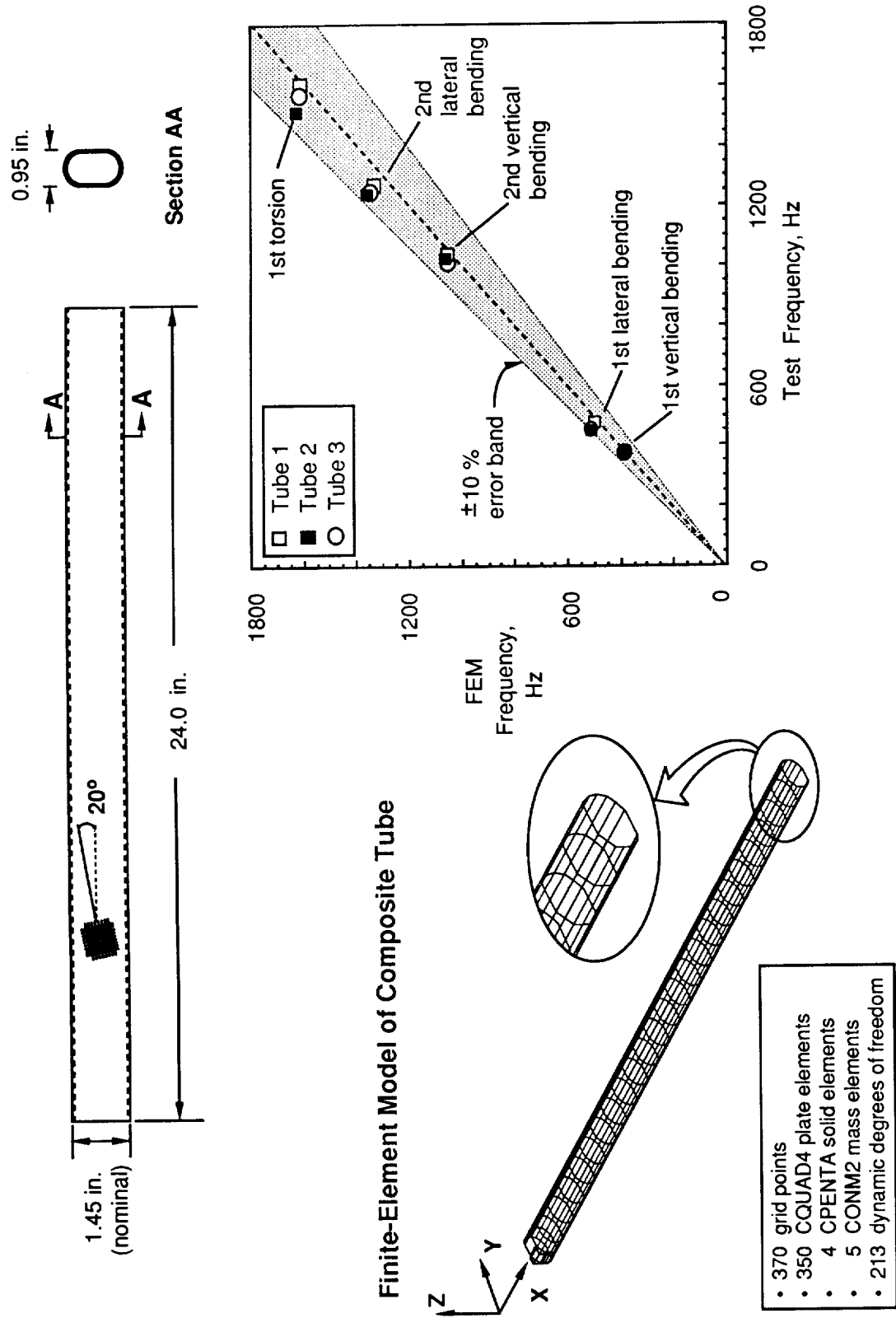


Figure 45 (b).

# PRELIMINARY DESIGN METHOD FOR PREDICTING THE EFFECTS OF DAMPING TREATMENT ON STRUCTURAL VIBRATIONS

Maurice I. Young  
VIGYAN Research Associates

Raymond G. Kvaternik  
Aeroservoelasticity Branch

RTOP 505-63-36

**Research Objective:** The objective of this effort is to achieve up to an order of magnitude reduction in resonant or near resonant structural forced vibrations by the addition of one or more localized and concentrated damping treatments and devices. This is possible since aircraft and similar types of structures are inherently lightly damped and small additional amounts of damping will yield large reductions in forced vibratory responses when the structure is responding at or near resonance.

**Approach:** The approach is to develop a simplified analytical preliminary design method which will predict the effect of localized, concentrated, and other types of damping treatments in increasing the various modal vibration fractions of equivalent viscous critical damping. An energy quotient analogous to Rayleigh's quotient for predicting undamped natural frequencies of vibration is utilized. The newly developed energy quotient employs the undamped modes of vibration to compute the generalized damping, mass, and stiffness terms which appear in the quotient to evaluate the influence of damping treatment types, locations, and magnitudes on the various modal damping fractions.

**Accomplishment Description:** Rigorous engineering analysis has demonstrated that the damped modal vectors of standard structural elements such as rods, beams, plates, and shells differ from the undamped modal vectors by small terms of the order of magnitude of the modal damping fraction or less. Accordingly, the simplified damping analysis yields predictions of  $\zeta_i$ , the  $i$ th mode damping fraction, well within one % or less of the exact magnitudes when the desired damping fractions are less than ten % of critical. In effect, the undamped modes are utilized to design the damped modes. An illustrative example of the preliminary design analysis method is given in the figure for both the bending and torsion of a uniform beam with a viscous damper at its center. The beam is simply supported for bending and clamped-clamped for torsion. The fundamental mode fractions of critical damping in both bending and torsion are computed for a range of desired viscous damping magnitudes. These results are compared with closed form analytical solutions for the beam. It is seen that this simplified method predicts the fractions of critical damping in the fundamental modes with excellent accuracy up to ten % of critical damping.

**Significance:** A simplified but accurate method of preliminary design analysis for damping structural vibrations has been developed. This method permits the structural designer to evaluate and employ damping treatments in conjunction with structural mass and stiffness considerations.

**Future Plans:** Analyses will be performed on several structural systems including a helicopter airframe to validate the design method. Results of these analyses will be compared with very detailed finite element type computations.

Figure 46 (a).



# PRELIMINARY DESIGN METHOD FOR PREDICTING THE EFFECTS OF DAMPING TREATMENT ON STRUCTURAL VIBRATIONS

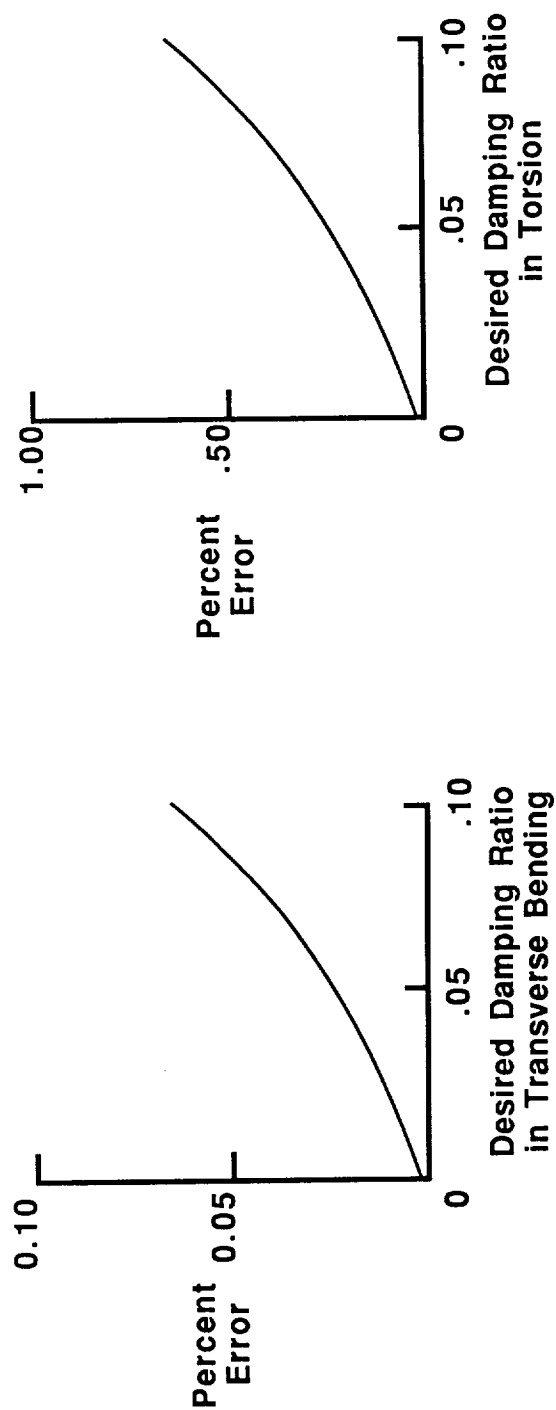
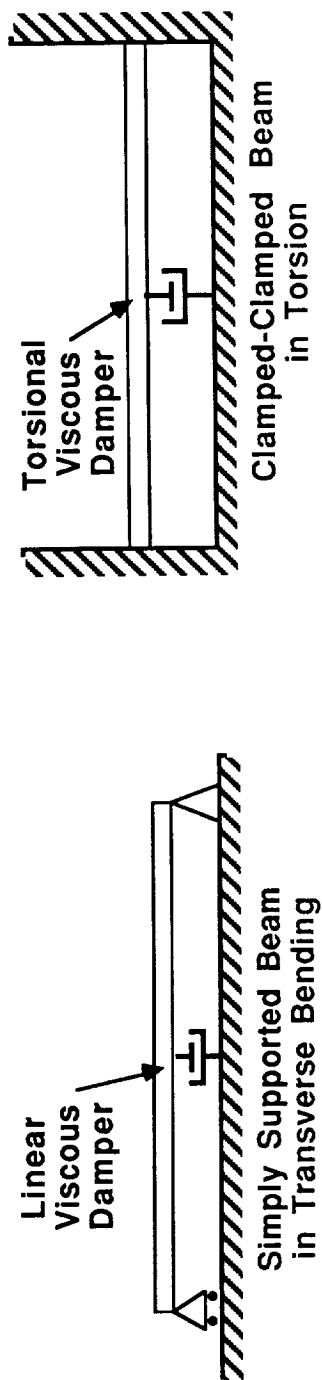


Figure 46 (b).

## EXTENSION-TWIST COUPLING CONCEPT DEMONSTRATED IN TDT

Renee C. Lake and Mark W. Nixon  
Aeroservoelasticity Branch

RTOP 505-63-36

**Research Objective:** Tiltrotor aircraft are designed to operate in both helicopter and airplane flight modes. This operational flexibility results in several conflicting design requirements. One such design requirement, which has significant effects on aerodynamic performance, is blade twist. Typically, the twist employed is a compromise between that required in the two different modes of flight. Performance could be improved if it were possible to vary the blade twist between the two flight modes. Tiltrotor aircraft typically vary rotor speed by about 20 percent between the two flight modes. This change in rotor speed induces a rather substantial change in the centrifugal force along the blade, which could be used to passively change the twist of an extension-twist-coupled (ETC) composite blade. Thus, the objective is to design an ETC blade to have optimum twist distributions in both airplane and helicopter flight modes.

**Approach:** Analytical and experimental studies have been designed to demonstrate the improvements in tiltrotor blade performance. These studies include whirl tests and wind tunnel tests conducted on a set of model-scale blades, with the primary goal of measuring blade twist as a function of rotor speed. Results from this experimental phase will be compared with those obtained from analytical studies using companion finite-element analysis models of the rotor blade.

**Accomplishment Description:** The set of composite model rotor blades used in this research investigation was manufactured from existing blade molds for a low-twist metal helicopter rotor blade, and was designed with a view towards establishing a preliminary "proof of concept" for extension-twist-coupled rotor blades. Wind tunnel testing of the set of extension-twist-coupled rotor blades was recently completed in the NASA Langley Transonic Dynamics Tunnel, following an abbreviated initial entry in the hover test facility. Data was obtained in hover for both a ballasted and unballasted configuration in ambient air conditions, and a ballasted configuration (only) in near-vacuum conditions. The blades were mounted on the Aeroelastic Rotor Experimental System (ARES) helicopter model and were spun through the 100-800 rpm range, with a corresponding sweep of collective pitch at 100 rpm intervals. Test results showed maximum twists of  $2.54^\circ$  and  $5.24^\circ$  in the ambient air condition for the unballasted and ballasted blade configurations, respectively. These results were compared with those obtained from a detailed non linear finite-element analysis of the rotor blade, which yielded maximum twists of  $3.02^\circ$  for the unballasted blade configuration, and  $5.61^\circ$  for the ballasted blade configuration. The maximum twist obtained experimentally from the ballasted blade configuration in the near-vacuum condition (not shown) was nearly unchanged from that of the corresponding ambient result.

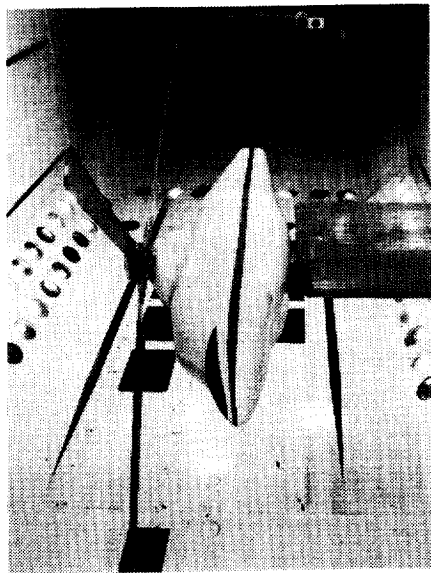
**Significance:** This task has demonstrated the feasibility of changing blade twist as a function of rotor speed using an extension-twist-coupled composite blade design.

**Future Plans:** The results from this test/analysis comparison will provide a basis for the future design of a highly-twisted extension-twist-coupled model blade for tiltrotor aircraft.

Figure 47 (a).

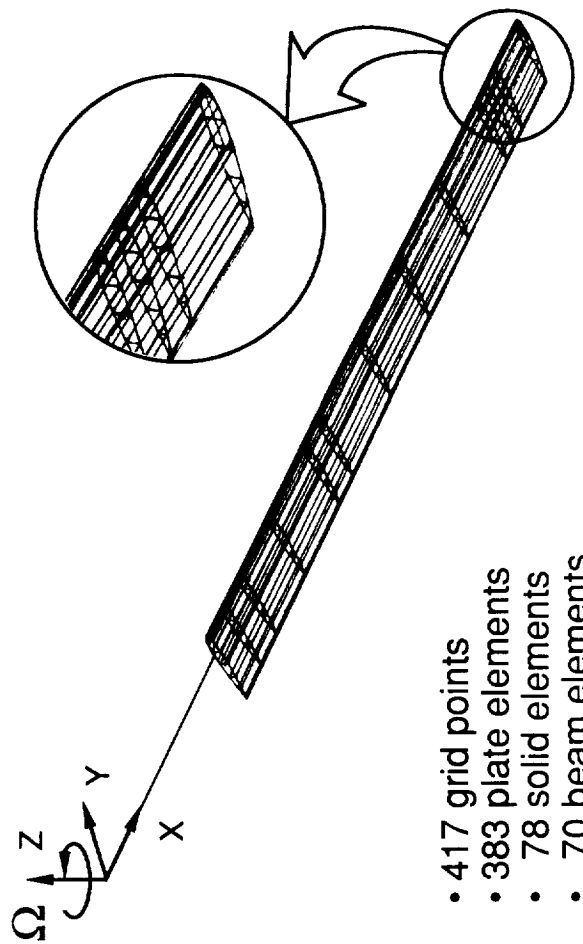
# Extension-Twist Coupling Concept Demonstrated In TDT

Composite Rotor Blades in TDT



ORIGINAL PAGE  
BLACK AND WHITE PHOTOGRAPH

Finite-Element Model



- 417 grid points
- 383 plate elements
- 78 solid elements
- 70 beam elements

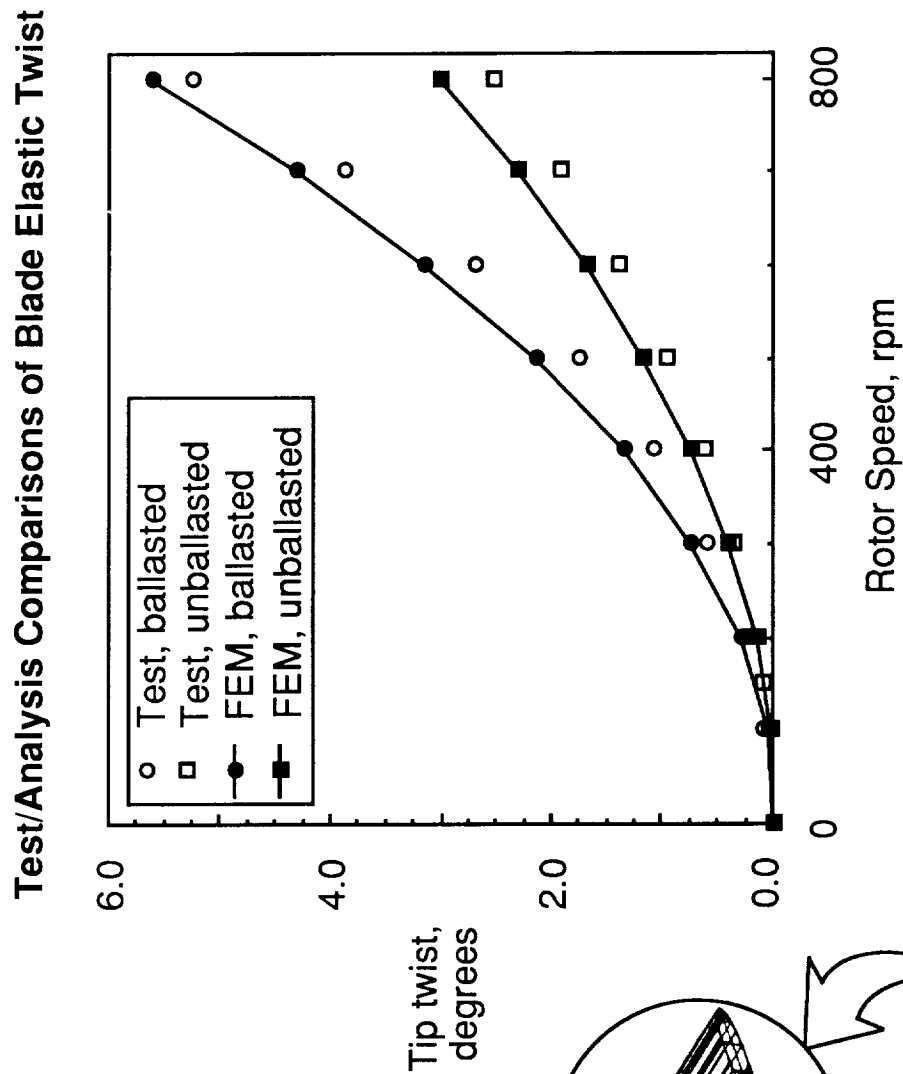


Figure 47 (b).

## GOVERNMENT/INDUSTRY ASSESSMENT OF DAMVIBS PROGRAM COMPLETED

Raymond G. Kvaternik  
Aeroservoelasticity Branch

RTOP 505-63-36

**Research Objective:** Excessive vibration is the most common technical problem to arise in the development of a new rotorcraft. With only a few exceptions, vibration problems have not been identified until flight test. Solutions at that stage of development are usually add-on fixes which adversely impact cost, schedule, and vehicle performance. Vibration predictions have not been relied on by the industry during design because of deficiencies in current vibration analysis methods. The NASA LaRC has underway a program, designated DAMVIBS (Design Analysis Methods for Vibration), with the objective of establishing the technology base needed by the industry for developing a superior finite-element-based dynamics design analysis capability for vibrations.

**Approach:** The scope of the DAMVIBS Program is depicted in the attached chart. Industry teams would carry out modeling, analysis, testing, and correlation studies on both metal and composite airframes. The finite-element models developed in these studies would then be used in follow-on studies to identify those "difficult components" which require refined representation in the FEM, to improve analyses for computing coupled rotor-airframe vibrations, and to develop techniques for airframe structural dynamics optimization. DAMVIBS was initiated in 1984 with the award of task contracts to major helicopter airframe manufacturers and was positioned as the initial phase of a new and broader-scope rotorcraft structural dynamics program which was initiated at LaRC at that time.

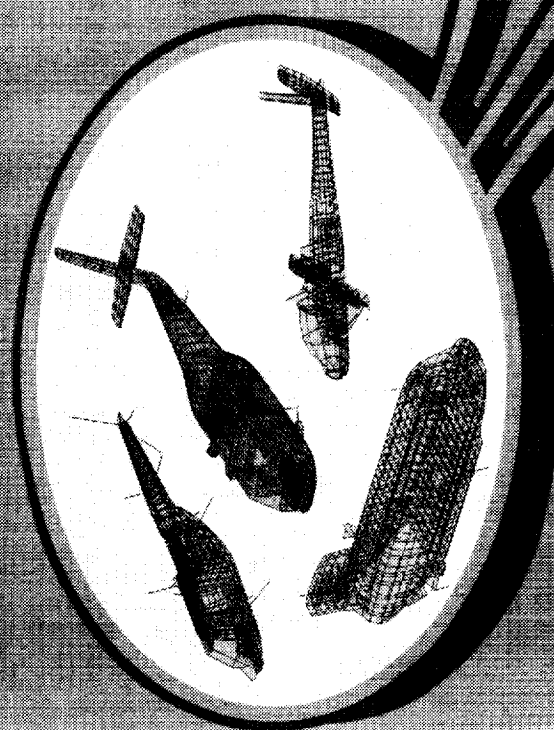
**Accomplishment Description:** Industry teams have formed FEMs, conducted ground vibration tests, and made test/analysis comparisons of six airframes (three metal and three composite). Difficult components studies of two airframes (metal and composite) have identified several important structural contributors to airframe vibrations. This work has led to improved modeling techniques, establishment of industry-wide FEM standards, and enhanced GVT methods. A comparative evaluation of industry codes for computing coupled rotor-airframe vibrations has indicated that current methods of analysis do not have the accuracy needed to rely on during design and identified this as an area needing more work. Five Government/industry work-in-progress meetings have been held in connection with the activities and have provided an effective forum for technology transfer. The fifth meeting included a session devoted to an assessment of the program, its benefits to the industry, and the identification of any work which still needs to be done. The assessments were made by the four industry participants and the NASA/Army sponsoring organizations at LaRC.

**Significance:** DAMVIBS has provided an important leadership role and focal point for structural dynamics research in government, industry, and academia. DAMVIBS has resulted in notable technical achievements and major changes in industrial design practice, all of which have significantly advanced the industry's capability to use and rely on FEM-based dynamics analyses during the design process.

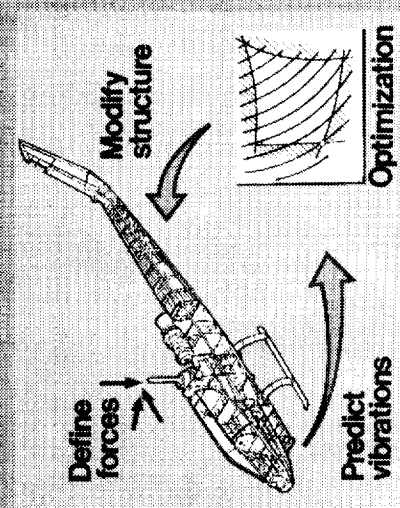
**Future Plans:** The DAMVIBS Program is to be phased out by F.Y. 1992. DAMVIBS areas which were identified as needing additional work are part of the current Langley Rotorcraft Structural Dynamics Program which has been refocused to serve as a bridge between the DAMVIBS Program and a new High-Speed Rotorcraft Program which NASA hopes to initiate in F.Y. 1995. The possibility of forming a rotorcraft structural dynamics council to provide a forum for continuing the Government/industry technology exchange which was started by the DAMVIBS Program will be explored.

Figure 48 (a).

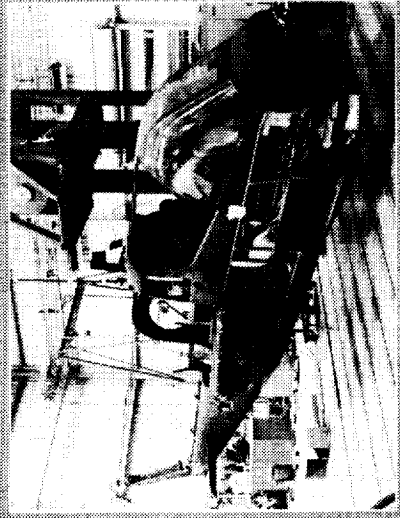
# GOVERNMENT/INDUSTRY ASSESSMENT OF DAVIDSON PROGRAM COMPLETED



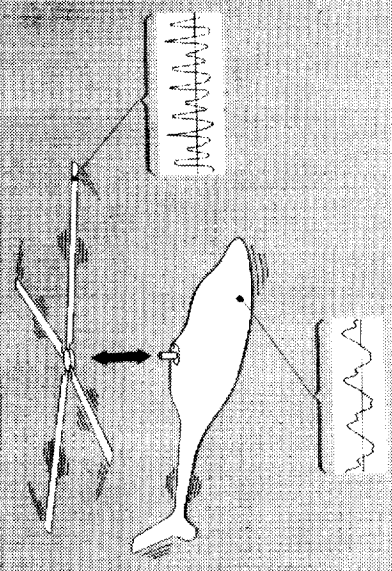
**Finite element modeling**



**Airframe structural optimization**



**Difficult component studies**



**Coupled rotor-airframe vibrations**

Figure 48 (b).

## DYNAMICS OPTIMIZATION CODE DEVELOPED FOR ROTORCRAFT AIRFRAME STRUCTURES

T. Sreekanta Murthy (LESC)  
Aeroservoelasticity Branch

RTOP 505-63-36

**Research Objective:** The objective of this research is to investigate the use of numerical optimization techniques for modifying structural design parameters such that vibrations on rotorcraft can be minimized, and to develop a computer code for performing this task.

**Approach:** The nonlinear mathematical programming approach is being pursued for optimization of rotorcraft airframe structures. The approach involves formulation of the vibration problem to find a minimum value of an objective function (eg., weight of the structure), under a specified set of structural response constraints (eg., limits on the forced response displacements or equivalent vibration levels at selected locations on the structure and limits on the range of allowable values of the natural frequencies of the structure), and with prescribed bounds on the modification of structural design parameters (eg., depth, width, thickness of the structural members). A solution to the optimization problem is sought via an iterative approach consisting of a sequence of computational tasks involving finite element analysis, sensitivity analysis, approximate analysis, and design change computations.

**Accomplishment Description:** A computer code called DYNOPT for dynamics optimization of structures has been developed. The code features a unique operational combination of the MSC/NASTRAN finite element structural analysis code extended to include steady-state dynamic response sensitivities and the CONMIN optimizer. DYNOPT has been organized into several independent modules which perform necessary optimization computational tasks indicated in the flow diagram of the accompanying figure. The program modules for the finite element analysis and the sensitivity analysis use solution sequences available in the MSC/NASTRAN Program in addition to newly-developed solution sequences to compute the structural responses and related sensitivity coefficients required in the solution of the optimization problem. The sensitivity analysis modules for steady-state forced response and structural weight are newly developed and are based on the Direct Matrix Abstraction Program instructions of the MSC/NASTRAN Program. The sensitivity analysis modules use the semi-analytical method to compute the sensitivity coefficients. The approximate analysis modules of the program compute the first-order Taylor series approximation of functions based on the use of direct, reciprocal, and hybrid forms of the design variables in the series expansion. Several other modules of DYNOPT have been developed to organize the data related to the objective function, constraints, and sensitivity coefficients, to interface optimizer algorithms with analysis programs, and to update finite element analysis section properties data during optimization iterations. Initial application of DYNOPT to several small as well as large structural problems, including the Bell AH-1G airframe, has been completed.

**Significance:** The newly developed capability permits design optimization studies on realistic rotorcraft configurations for minimization of structural vibration.

**Future Plans:** Optimization studies using DYNOPT are continuing. Emphasis will be placed on application to other rotorcraft configurations to further assess and validate the code.

Figure 49 (a).

# DYNAMICS OPTIMIZATION CODE DEVELOPED FOR ROTORCRAFT AIRFRAME STRUCTURES

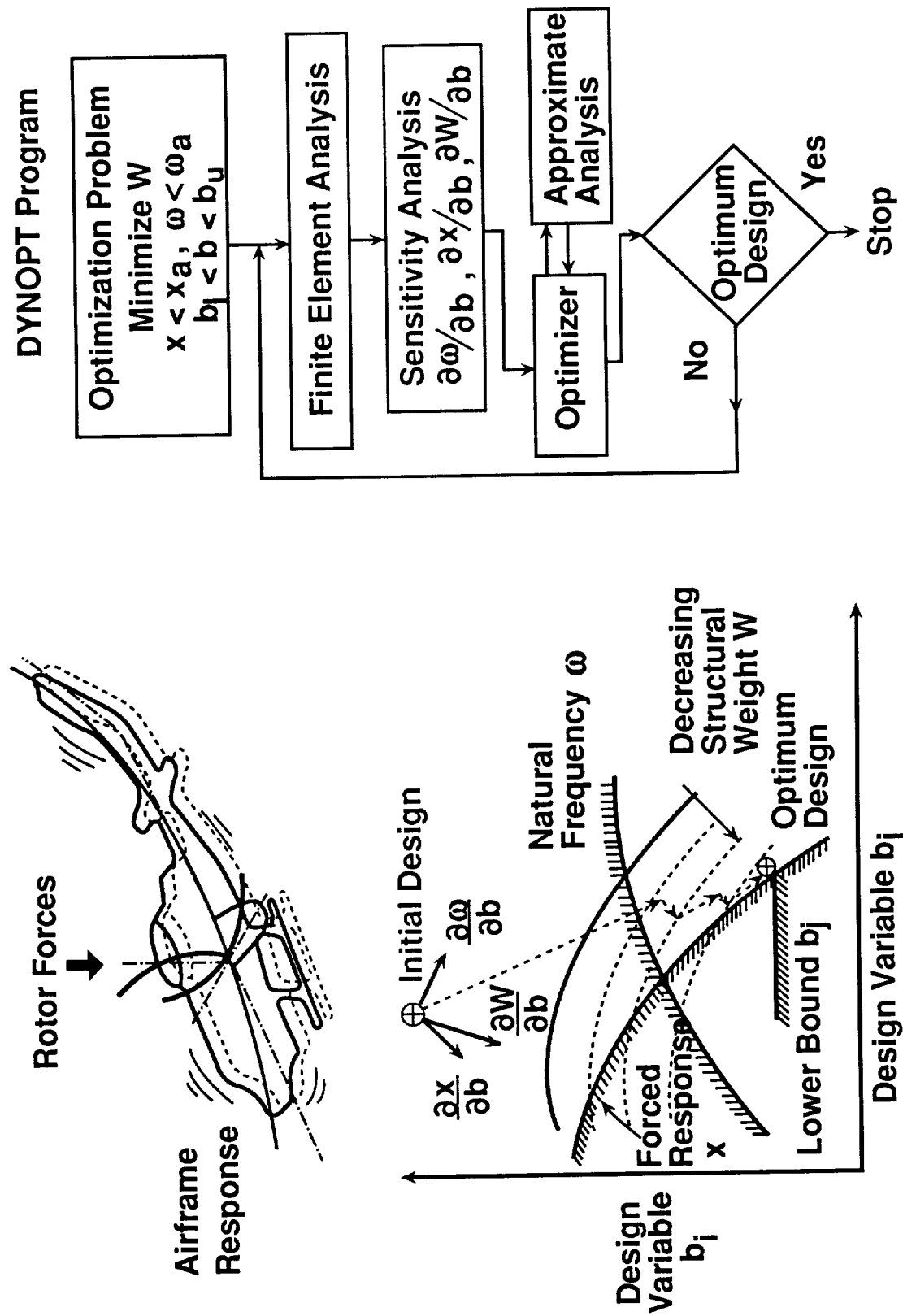
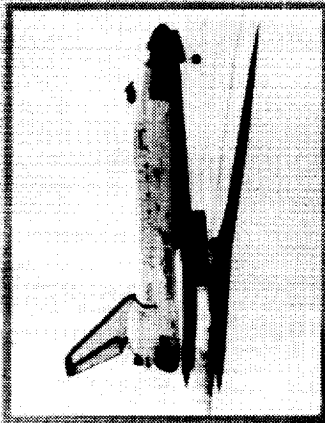


Figure 49 (b).



## LANDING AND IMPACT DYNAMICS BRANCH



### Research opportunities

- Reduce fatalities
- Improve landing gears, tires and runways
- Reduce crash loads with loading-limiting structure

Figure 50.



# LANDING DYNAMICS FUTURE PLANS (FY 91-95)

## GOAL

ENHANCED GROUND HANDLING SAFETY AND PERFORMANCE

## KEY OBJECTIVES

- CONDUCT LABORATORY AND ALDF TESTS OF NEW TIRE DESIGNS AND ACTIVE CONTROL LANDING GEAR CONCEPTS



- DEVELOP TIRE AND LANDING GEAR ANALYSIS TOOLS



Figure 51 (a).

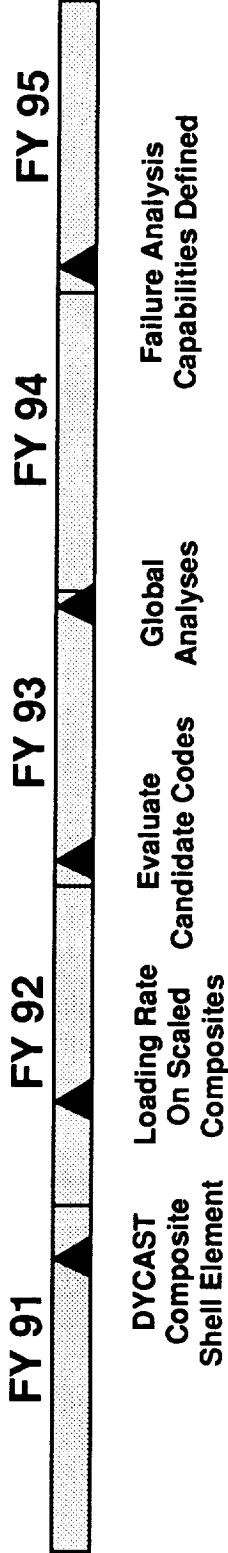
## LANDING DYNAMICS FUTURE PLANS (FY 91-95)

## GOAL

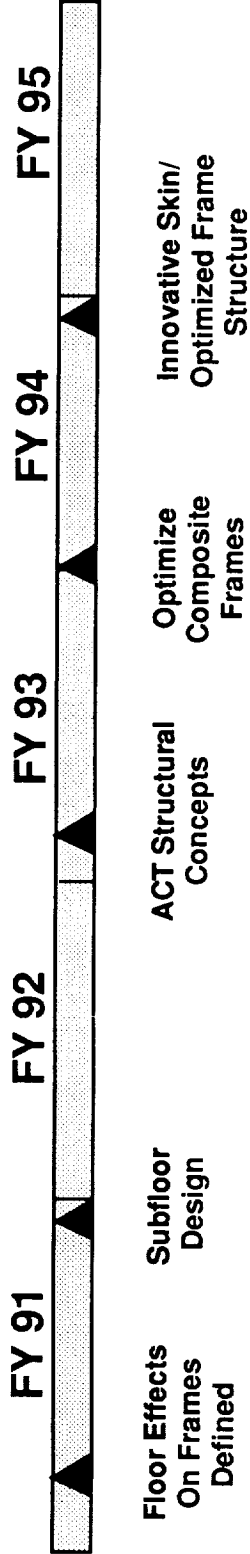
# FUNDAMENTAL UNDERSTANDING OF COMPOSITE CRASH BEHAVIOR AND IMPROVED CRASHWORTHY DESIGNS

## KEY OBJECTIVES

- **DEVELOP NONLINEAR STRUCTURAL ANALYSIS METHODS**



- **DEFINE DATA BASE FOR COMPOSITE STRUCTURES**



**Figure 51 (b).**

# LANDING DYNAMICS FUTURE PLANS (FY 91-95)

GOAL

FUNDAMENTAL UNDERSTANDING OF COMPOSITE CRASH BEHAVIOR  
AND IMPROVED CRASHWORTHY DESIGNS

KEY OBJECTIVES

- CONDUCT FULL-SCALE TESTS OF COMPOSITE AIRFRAMES

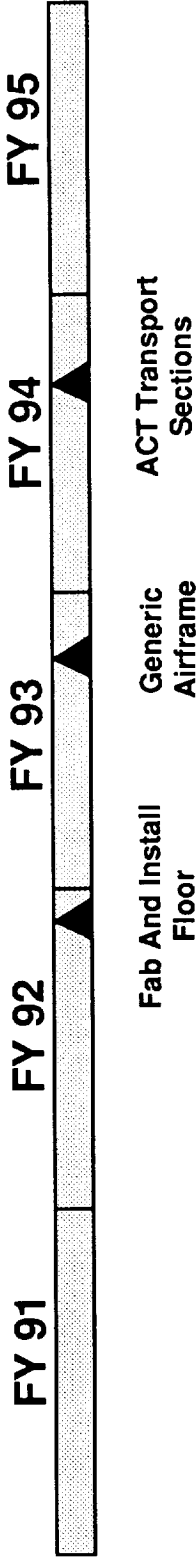


Figure 51 (c).

# COMMONALITY IN FAILURE BEHAVIOR IDENTIFIED FOR METAL AND COMPOSITE AIRCRAFT STRUCTURES UNDER CRASH LOADS

Huey D. Carden  
Landing and Impact Dynamics Branch

RTOP 505-63-01

**Objective:** A major objective of the impact dynamics research program is to assess through a systematic combination of analytical and experimental studies the failure and response behavior of generic metal and composite aircraft structures under simulated crash loads. The results of these studies will yield the understanding of crash dynamics necessary to design more crashworthy airframe structures.

**Approach:** Static and dynamic tests were conducted on a variety of metal and composite aircraft structures and components to determine their response and failure behavior under simulated crash conditions. Nonlinear finite-element models were formulated and used to provide insight into the fundamental physics of the behavior of the structures under crash loads and to provide analytical results for correlation with the experimental results.

**Accomplishment Description:** Shown in the attached figure is a normalized analytical moment (strain) distribution for a typical composite fuselage frame under vertical load. Superimposed on the distribution is the location of the observed experimental failure positions for metal and/or composite full-scale panels, aircraft sections, frames, and subfloors. It should be noted that there is a commonality in the location of the failures for the various aircraft structures which coincide with the maximums in the moment distribution of the typical frame under vertical loading. As shown on the sketch at the right, the angular locations occur at the point of initial contact or impact with the ground and at approximately 50° to 60° up both sides of the structure. As indicated at the left, these locations correspond to the points of maximum moment (strain) for the loaded structure.

**Significance:** With the discrete failure locations noted for cylindrical structures under vertical loads, energy absorption decreases dramatically emphasizing the need to provide structural concepts which are designed to provide some energy absorbing mechanism in the design. Additionally, knowing that these aircraft structures have a commonality in failure behavior may provide designers, dynamists, and analysts with useful information to allow newer, more energy absorbing structures to be designed, provide knowledge of where failures most probably will occur, and allow better analytical models to be formulated for analysis and prediction.

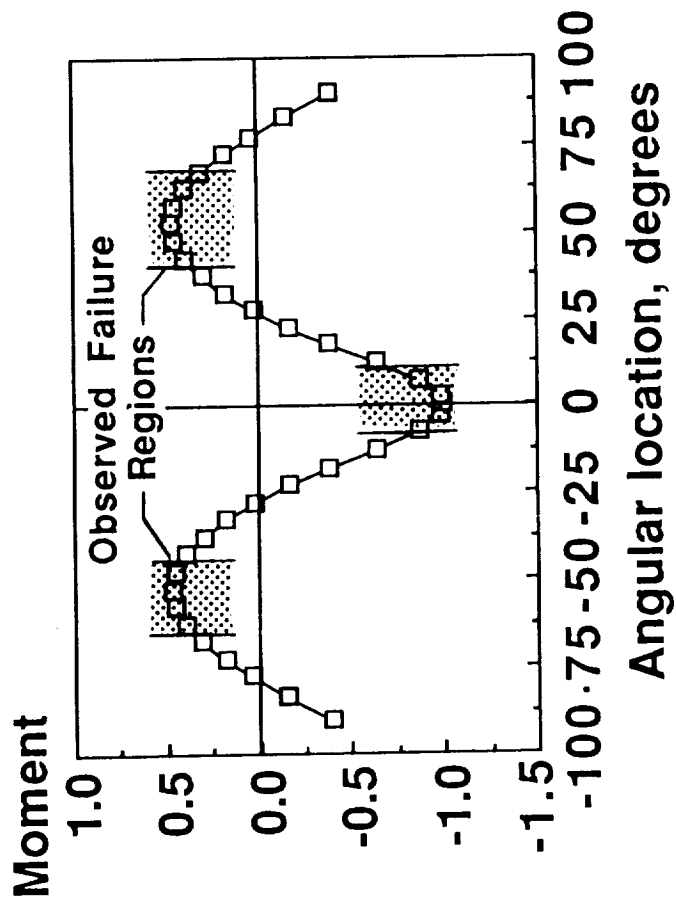
**Future Plans:** Publish reports on the research results and continue research to add to the database. Conceive new concepts for better energy absorption and evaluate the effectiveness of these concepts.

Figure 52 (a).

# COMMONALITY IN FAILURE BEHAVIOR IDENTIFIED FOR METAL AND COMPOSITE AIRCRAFT STRUCTURES UNDER CRASH LOADS

## Full-Scale Transport Sections, Single Composite Frames, Composite Subfloors (With and Without Skin)

### Moment distribution



### Failure Locations

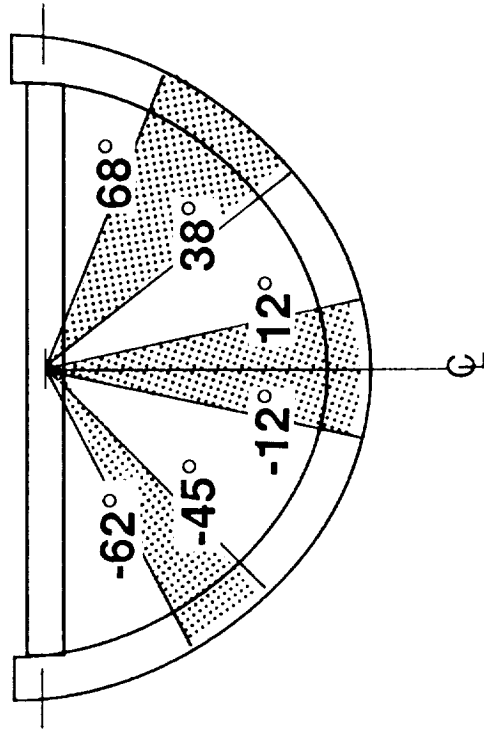


Figure 52 (b).

# IMPACT TESTS USED TO QUALIFY HONEYCOMB ENERGY ABSORBING ATTENUATORS FOR CETA EMERGENCY BRAKE

Edwin L. Fasanella and Lisa E. Jones, Lockheed Engineering and Sciences Co.  
Karen E. Jackson, U. S. Army Aerostructures Directorate  
Landing and Impact Dynamics Branch

RTOP 505-63-01

**Research Objective:** The CETA cart is an advanced mobility concept designed to transport up to two astronauts and additional equipment on the space station. As part of design evaluation, a flight experiment consisting of a CETA cart attached to a 50 ft. long monorail will be operationally tested in the Space Shuttle cargo bay during an upcoming flight. Because safety considerations require that an emergency stopping device be installed at the end of the monorail to bring the astronauts to a controlled stop in the event of a brake failure, a research study was undertaken to refine an emergency braking system proposed for use on CETA.

**Approach:** A device incorporating a crushable honeycomb column as the energy dissipating mechanism was designed by the Systems Engineering Division for use as the emergency stopping device. The column consists of four six-inch-long segments of 75 psi honeycomb, separated by 1.5 inch diameter washers. A series of impact tests was performed on various configurations for the honeycomb columns to determine which design provided the required stopping force of 100 lbs and energy dissipation of 1560 in-lbs per energy absorber. The impact tests were conducted using the small vertical drop tower (illustrated in the lower left in the figure) located at the Impact Dynamics Research Facility (IDRF). The honeycomb energy absorbing columns were supported inside a test sleeve which provided sufficient radial clearance to allow the specimen to expand as it compressed. The impact load was provided by a mass car with an attached plunger wa velocity of 6 ft/sec. A load platform under the test sleeve measured the stopping force of the honeycomb and a string potentiometer measured the vertical crush of the test specimen.

**Accomplishment Description:** Twenty six impact tests were performed from which load-displacement, energy-displacement, average force-displacement, and velocity-time curves were generated to evaluate the performance of the various honeycomb configurations. Illustrative load-displacement results are shown on the right of the figure. Analysis of the data and inspection of the post-crushed specimens (shown at the upper left in the figure) indicated that the honeycomb columns tended to buckle under impact. This phenomenon may be attributed to excessive clearance between the honeycomb column and the test sleeve, and to the high aspect ratio (length to width) of the column geometry. Buckling inhibits the efficiency of the energy absorbing tubes since the force drops and then builds to a high level as the washers rotate and jam inside the test sleeve. During manufacture, precise alignment of the washer and honeycomb cylinder axes is required to prevent buckling. Aluminum and teflon washers were tested with the teflon washers providing more uniformity in performance. The honeycomb specimens having a standard core with a foil wrap had better energy absorbing characteristics than the tube core specimens.

**Significance:** Based on the results of impact tests, a honeycomb energy absorbing column with standard core, foil wrapping, and teflon washers was chosen for the CETA flight experiment.

**Future Plans:** Document this research in a NASA TM.

Figure 53 (a).

# IMPACT TESTS USED TO QUALIFY HONEYCOMB ENERGY ABSORBING ATTENUATORS FOR CETA EMERGENCY BRAKE

## HONEYCOMB SPECIMENS

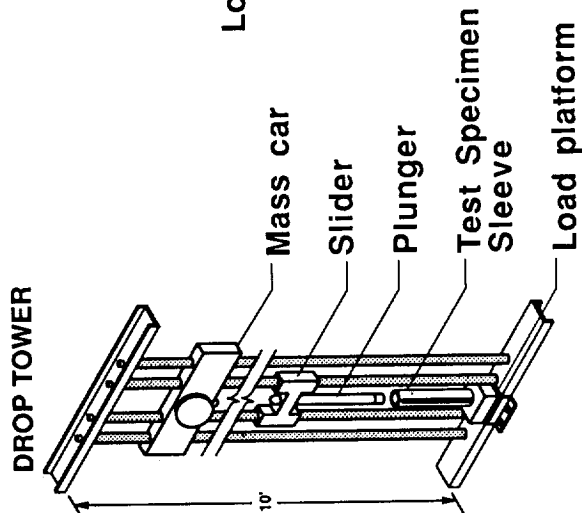
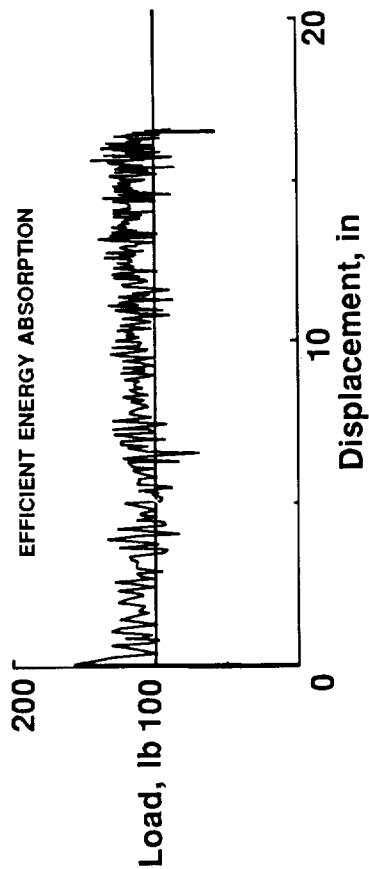
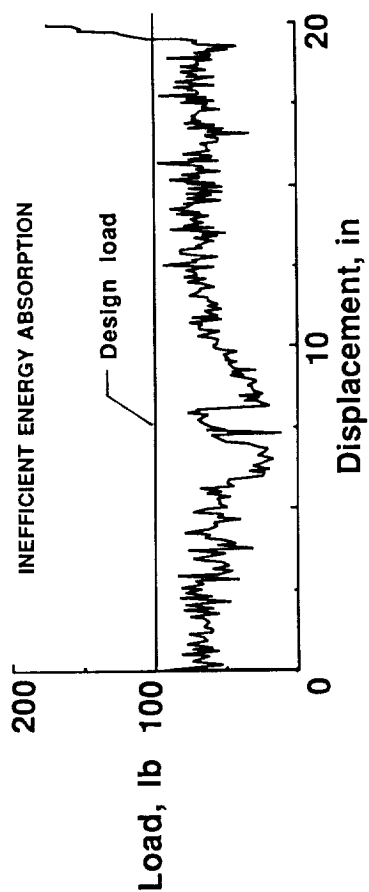
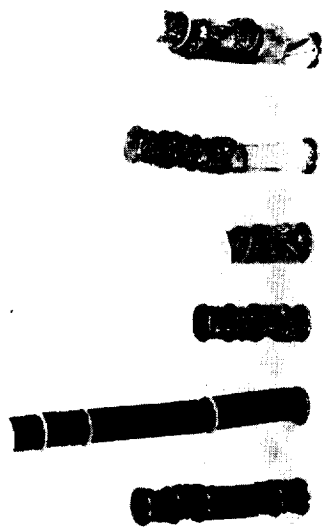


Figure 53 (b).

## COMPARISON OF PREDICTED AND EXPERIMENTAL SCALE EFFECTS IN STRENGTH OF COMPOSITE BEAMS

Karen E. Jackson, Landing and Impact Dynamics Branch

RTOP 505-63-01

**Research Objective:** A research program was developed to determine the effectiveness of scale model testing for predicting the static large deflection response and failure of composite beams subjected to an eccentric axial compressive load. A main objective is to characterize scaling effects in the behavior of the beams such that measurements made on subscale models will accurately predict prototype response.

**Approach:** Static tests were conducted on  $1/6$ ,  $1/4$ ,  $1/3$ ,  $1/2$ ,  $2/3$ ,  $3/4$ ,  $5/6$ , and full scale replica model beams of AS4/3502 graphite-epoxy composite material. Beams having unidirectional, angle ply, cross ply, and quasi-isotropic laminate stacking sequences were tested under an eccentric axial compressive load which promotes large flexural deformations and global beam failures. Vertical load, end displacement of the beam specimen, and tensile and compressive strain at the beam midpoint were recorded until catastrophic failure occurred. Normalized load versus deflection results indicated that classical scaling laws apply for linear elastic response, even for large rotations and deformations. However, a significant scale effect in ultimate strength of the composite beams was observed experimentally. Strength values for each of the scale model beams were normalized by the full-scale value and plotted versus scale factor, as shown in the figure. If no scale effect in strength was present, all of the data would fall on the line drawn at 1.0 in each plot. Scaled beams are stronger than the full-scale prototype for each of the laminates tested.

**Accomplishment Description:** Two different analytical models, one based on a Weibull statistical approach and the other on a fracture mechanics theory, were applied to the experimental failure data as strength ratio versus scale factor (as shown in the figure) in an attempt to predict the observed scale effect in strength. The use of statistical techniques for modeling the size effect in strength of brittle materials is based on the observation that these materials are flaw-sensitive. Since the presence of imperfections can be statistical in nature, it is reasonable to assume that larger specimens will exhibit lower strength simply because there is a higher probability that a strength-critical flaw is present in the greater volume of material. The Weibull model incorporates a flaw density parameter,  $b$ , which is a measure of the scatter in the strength data. If  $b$  is determined empirically from two specimens of differing size, then the strength of geometrically similar models can be predicted. The fracture mechanics model is derived by including the critical stress intensity factor in a dimensional analysis. For each of the four laminate types tested, the Weibull statistical model gives better predictions of the strength degradation with increasing specimen size than the fracture mechanics model. However, the Weibull model depends on the empirical flaw density parameter which is not a material constant.

**Significance:** The observed strength scale effect cannot be predicted by standard composite failure criteria such as maximum stress, maximum strain, or tensor polynomial, since these criteria do not incorporate some measure of absolute specimen size. Strength scale effect must be modeled so that results on laboratory coupon specimens can be properly "scaled up" to predict full-scale behavior.

**Future Plans:** An extension of the scaling research is planned to identify the effects of pre-existing damage in unloaded beams on the strength scale effect. In addition, a more refined analysis which incorporates some measure of absolute specimen size and the mechanism of failure is needed to predict the strength scale effect of various composite laminate stacking sequences.

Figure 54 (a).



# COMPARISON OF PREDICTED AND EXPERIMENTAL SCALE EFFECTS IN STRENGTH OF COMPOSITE BEAMS

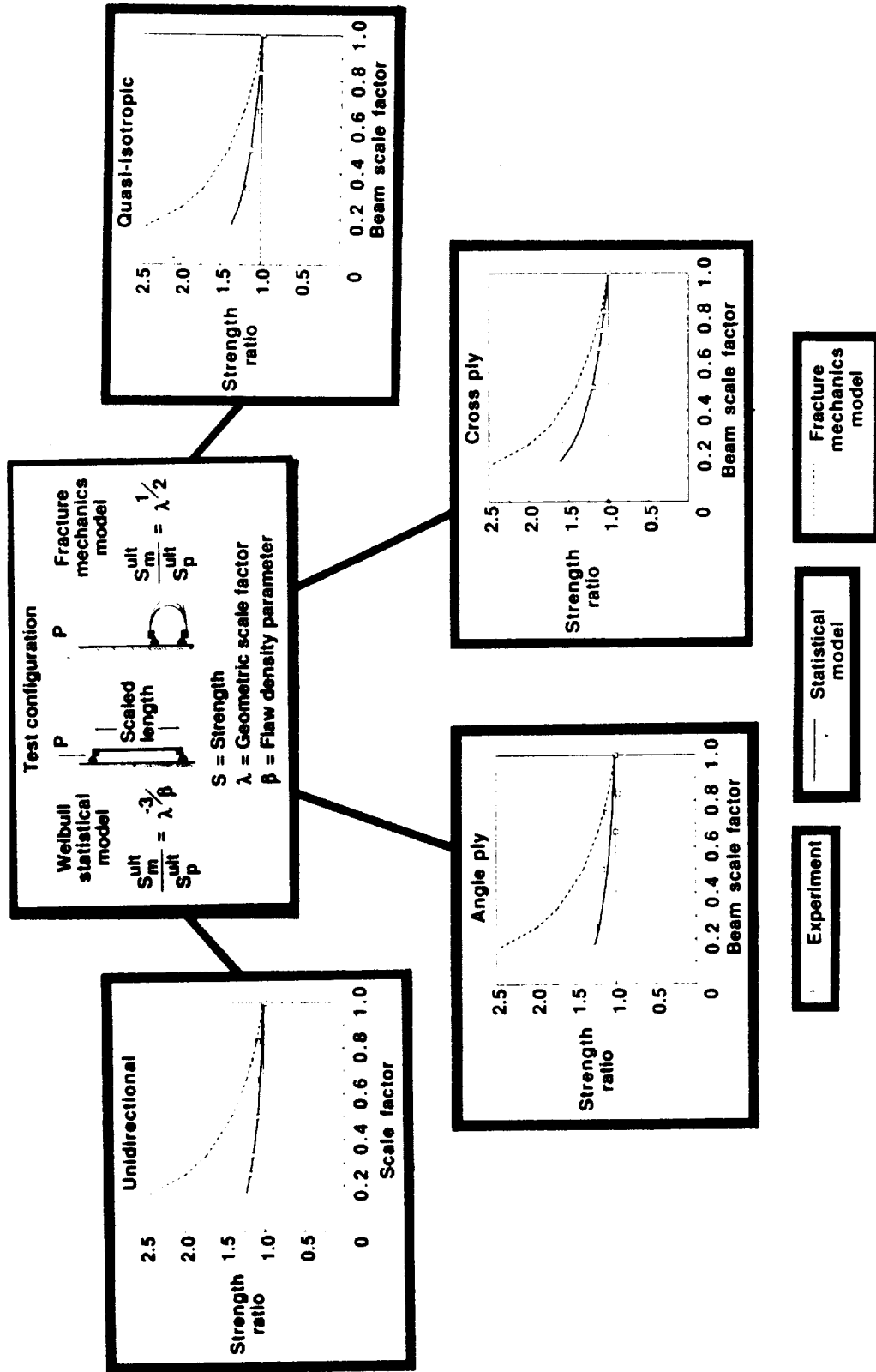


Figure 54 (b).

# VARIOUS NONLINEAR FINITE ELEMENT ANALYSIS TOOLS COMPARED USING EXPERIMENTAL DATA FROM COMPOSITE BEAM COLUMN STUDY

Edwin L. Fasanella, Lockheed Engineering and Sciences Co.  
Karen E. Jackson, U. S. Army Aerostructures Directorate  
Landing and Impact Dynamics Branch

RTOP 505-63-01

**Research Objective:** The purpose of this research is to study the static, large deflection response and failure of a graphite-epoxy composite beam-column using nonlinear finite element codes designed for analysis of complex structural impact problems. Comparisons of the analytical models with an exact solution and experimental data will be made to evaluate the performance of various elements for accuracy and ease of implementation.

**Approach:** The eccentrically loaded graphite-epoxy beam-column configuration, shown in the figure, was chosen as a test case for comparison of analytical codes for several reasons. The beam-column represents a simple structure that exhibits the fundamental bending and failure characteristics of the lower portion of an aircraft fuselage subjected to vertical forces during a crash. In addition, an exact solution of the static beam-column problem exists and a large amount of experimental data has been generated for composite beams of various sizes and different laminate stacking sequences. For this analysis, a 24 ply unidirectional graphite-epoxy (AS4/3502) beam was chosen with a gage length of 15 inches, width 1.5 inches, and thickness of approximately 0.13 inches. As shown in the figure, the beam is supported in hinges at the top and bottom which offset the axial load to generate a combined bending and axial loading state. The bottom hinge was fixed with only one rotational degree of freedom, while the top hinge is allowed to translate vertically and to rotate. The finite element codes DYCAST (Dynamic Crash Analysis of Structures) developed by Grumman and the NIKE/DYNA codes developed by the Lawrence Livermore Laboratories were used in this analysis. Both beam and plate elements were used and compared with experiment data and the exact solution.

**Accomplishment Description:** A comparison of the DYCAST beam model with the exact solution and experimental data is shown in the figure on the lower left. The DYCAST beam analysis corresponds almost identically with the exact solution and gives excellent agreement with the test data, even for very large displacements and loads. The figure at the bottom right shows load-deflection responses from plate models generated using NIKE and DYCAST codes and (lower center) a beam model using NIKE. The DYCAST plate model, which used triangular members, was considerably stiffer than the DYCAST beam solution and consistently overpredicted the static load-deflection response by about 10 %. The NIKE rectangular plate model showed good agreement with the exact solution for small deflections. However, as the load increased, the NIKE plate solution stiffened and deviated from the exact response. In contrast, the NIKE beam model overpredicted the small deflection beam response as did the DYCAST plate model. The NIKE beam model approached the exact solution for larger displacements.

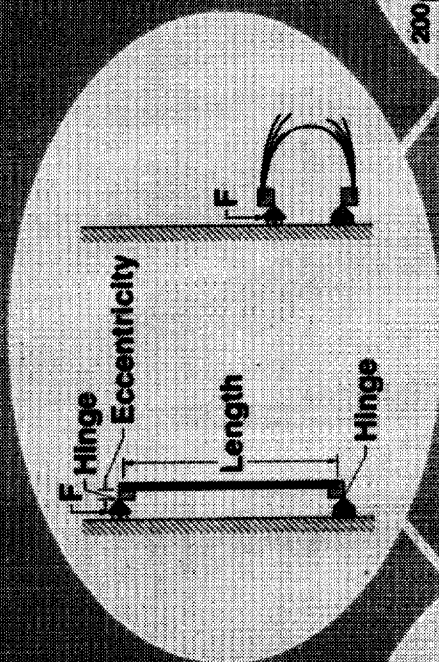
**Significance:** Results show that both DYCAST and NIKE codes can be used to model the eccentrically loaded graphite-epoxy beam-column problem. The DYCAST beam model and the NIKE plate model gave the best correlation, respectively, with the exact solution. DYCAST required little computational effort whereas the NIKE plate model required considerable computational effort.

**Future Plans:** Document this research in a technical paper.

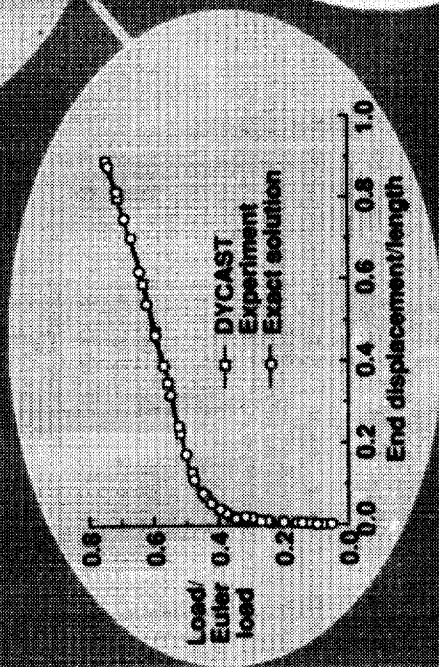
Figure 55 (a).

# VARIOUS NONLINEAR FINITE ELEMENT ANALYSIS TOOLS COMPARED USING EXPERIMENTAL DATA FROM COMPOSITE BEAM COLUMN STUDY

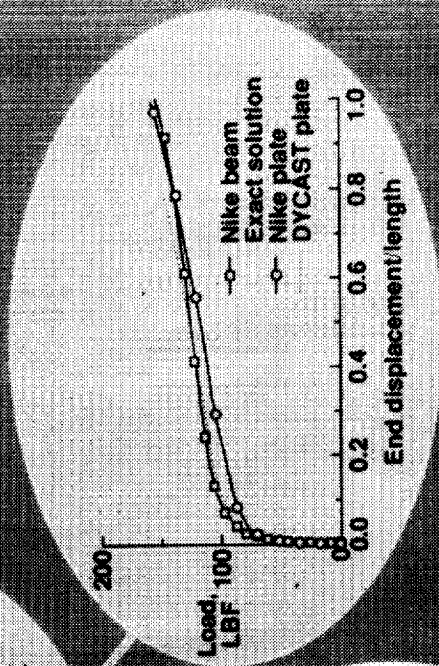
Schematic of beam column experiment



Comparison of exact solution, DYCAST analysis and experiment



Comparison of Nike, exact and DYCAST analysis



Deformed beam (Nike plate model)

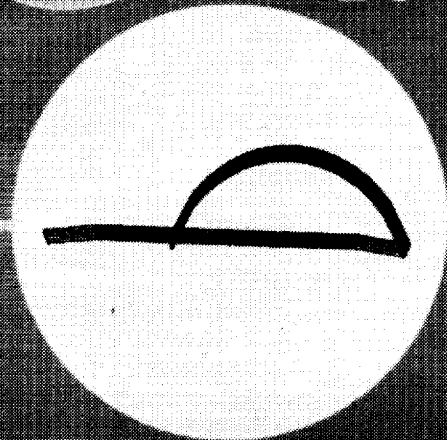


Figure 55 (b).

# EFFECT OF FLOOR LOCATION ON FAILURE BEHAVIOR OF COMPOSITE AIRCRAFT FUSELAGE FRAME CONCEPT DETERMINED ANALYTICALLY

Lisa E. Jones and Huey D. Carden  
Landing and Impact Dynamics Branch

RTOP 505-63-01

**Objective:** Experimental and analytical studies are part of the composite impact dynamics research to generate a data base on the behavior of composite structures under crash loads. Part of the effort has been the determination of the effect of the floor vertical attachment position on the response and failure of generic composite fuselage frame concepts.

**Approach:** Nonlinear finite-element models of a six-foot diameter composite fuselage frame concept were formulated. Static loads were applied to the frame/floor simulation to determine the load-deflection response of the composite frames. Failure loads and strain distributions were determined using the models in which the location of the simulated floor was moved to several locations on the circumference of the frame.

**Accomplishment Description:** As shown in the attached figure, the load with the finite element which produced failure of a composite I-frame varies essentially linearly as a function of 1/arc length of the loaded lower portion of the frame. The linear variation with 1/arc length of the ring or arch is also predicted by closed form solutions for loaded rings/arches. As may be noted, the shorter frame segments produced the highest failure loads. Typical circumferential strain distributions (at a 500 lbf load) for the composite fuselage frame for different floor locations was similar to the distribution for the floor located at the diameter (Position 1). Although the strain distributions associated with the lower floor locations were compressed horizontally between the ends of the floor attachment points, failure still occurred at the point of ground contact and at  $\pm$  positions up the frame from the point of ground contact.

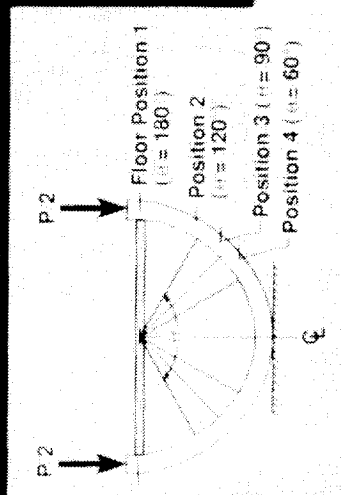
**Significance:** Since less and less material below the lower circumferential floor positions is involved in carrying the load, the energy absorption requirements are more critical for the shallow floor positions. With the widely separated, discrete failure locations associated with the composite frame concepts, there is a need to provide innovative structural concepts which have some inherent, more efficient energy absorbing mechanism(s) in the subfloor design.

**Future Plans:** Conduct experimental static and dynamic tests to verify the analytical predictions for the composite fuselage frame concepts.

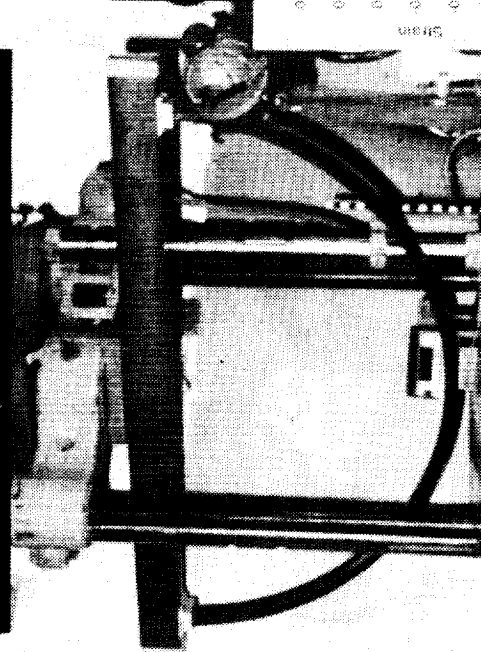
Figure 56 (a).

# EFFECT OF FLOOR LOCATION ON FAILURE BEHAVIOR OF COMPOSITE FUSELAGE FRAME CONCEPT DETERMINED ANALYTICALLY

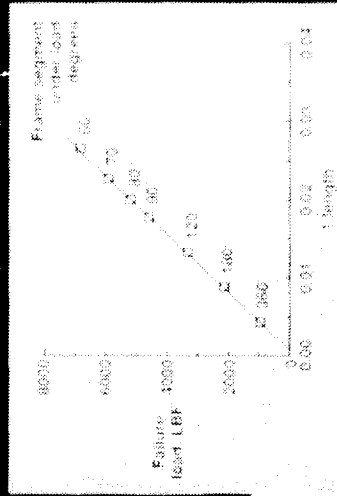
Load and floor position



Composite I-frame



Load producing failure



Typical strain at 500 LBF

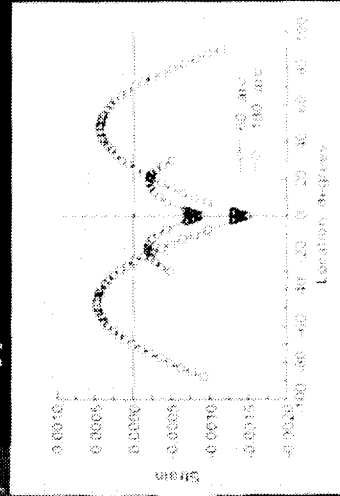


Figure 56 (b).

## SENSITIVITY DERIVATIVES DEVELOPED TO STREAMLINE FUTURE TIRE DESIGN PROCEDURES

Ahmed K. Noor and Jeanne M. Peters  
University of Virginia

John A. Tanner and Martha P. Robinson  
Landing and Impact Dynamics Branch

RTOP 505-63-01

**Research Objective:** The objective of this research is to develop a family of computationally efficient analysis tools that will facilitate tire and landing gear analyses and streamline the tire design process.

**Approach:** A computational procedure has been developed for evaluating the analytic sensitivity derivatives of tire response with respect to material and geometric parameters of the tire. The tire is modeled as a two-dimensional laminated anisotropic shell with the effects of variation in material and geometric parameters included. The computational procedure is applied to the 32 x 8.8 Space Shuttle orbiter nose-gear tire subjected to a uniform inflation pressure load.

**Accomplishment Description:** The uninflated and inflated profiles of the Space Shuttle orbiter nose-gear tire are shown in the figure. The effect of the 300 psi inflation load is to force the tire profile to grow radially outward as denoted by the dashed line in the figure. The tire carcass is composed of ten plies of rubber and nylon cords and covered with an inner liner and a natural rubber sidewall and tread outer layer. The carcass plies are constructed with nylon cords of two different diameters. The two inner plies contain the smaller diameter cords, denoted by  $d_1$ , and the remaining plies contain the larger diameter cords, denoted by  $d_2$ . Also presented in the figure is the variation in radial displacement,  $W$ , along the tire meridional coordinate,  $\xi$ , and the variations of the analytic derivatives of the radial displacement with respect to cord diameter,  $d$ ; Young's modulus of the nylon cord,  $E_c$ ; and Young's modulus of the rubber,  $E_r$ . The radial displacement results indicate that the peak profile growth of the Shuttle nose-gear tire due to inflation pressure occur along the tire equator ( $\xi = 0$ ) with secondary peaks along the tire sidewall. The sensitivity derivatives indicate that increasing cord diameter or the Young's modulus of the nylon cord or rubber decreases the radial growth of the tire due to inflation. Changes to the cord diameter and modulus have a greater effect along the tire equator and changes to the rubber modulus have a greater effect in the tire sidewall.

**Significance:** The development of analytic sensitivity derivatives of tire response with respect to tire material and geometry parameters will provide tire industry with powerful analytical tools for tire design and analyses. These derivatives will eventually provide the framework for tire optimization studies that have the potential to significantly enhance the tire design process.

**Future Plans:** Future activities in tire modeling will apply this computational procedure to more complex tire loading problems such as static contact and rolling contact with braking and cornering forces applied. The family of sensitivity derivatives will also be expanded to include a wider range of tire construction and response parameters.

Figure 57 (a).

# SENSITIVITY DERIVATIVES DEVELOPED TO STREAMLINE FUTURE TIRE DESIGN PROCEDURES

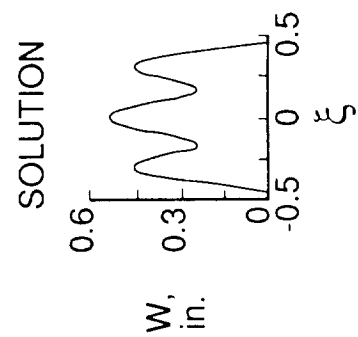
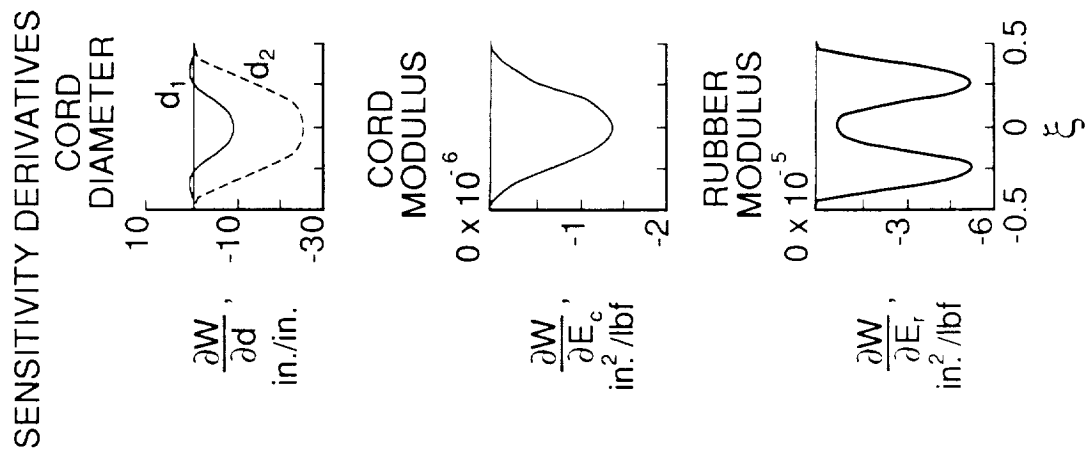
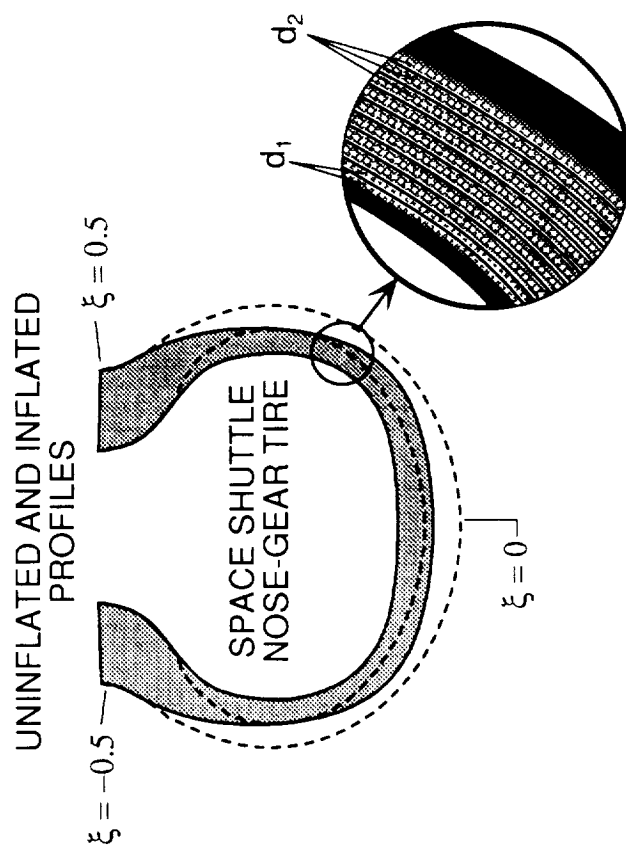


Figure 57 (b).

## VARIABLE YAW SYSTEM REDUCES TIRE CHARACTERIZATION TEST TIME

Robert H. Daugherty  
Landing and Impact Dynamics Branch

RTOP 505-63-10

**Research Objective:** To increase the productivity of the Aircraft Landing Dynamics Facility (ALDF) so that landing gear and tire research programs can be completed in a more timely manner.

**Approach:** Because of the unique capabilities of the ALDF, many challenging test programs that are otherwise difficult or impossible to conduct safely elsewhere are scheduled at the facility. Thus, attempts to streamline test programs result in increased productivity. A variable yaw system, shown in the figure, was designed and installed on the ALDF test carriage to permit a range of yaw angles to be tested during a single run. Prior to this, only a single yaw angle was used during a test run. The variable yaw system allows yaw angle to vary from  $0^\circ$  to  $16^\circ$  or anywhere in between. It also allows for static yaw capability as before.

**Accomplishment Description:** Initial tests with the variable yaw system were aimed at evaluating how high a yaw rate was possible while not compromising the quality of side force data compared to a fixed yaw angle. These tests showed that yaw rates as high as  $5^\circ$  per second were satisfactory. The plot in the figure shows good response of the side force coefficient to the varying yaw angle. A typical set of tire characterization tests may involve five or six yaw angles and three to four vertical loads. Because yaw angle used to be fixed during tests, five or six runs would be needed to characterize the cornering behavior of the tire. Use of the variable yaw system with fixed vertical load accomplishes the same objective with only three or four runs for each test surface. Thus this system can reduce test time by up to 40 % during certain test programs.

**Significance:** This additional capability will enhance the productivity of the ALDF.

**Future Plans:** Most tire testing conducted in the future at the ALDF will make use of the variable yaw system to minimize test time.

Figure 58 (a).



# VARIABLE YAW SYSTEM REDUCES TIRE CHARACTERIZATION TEST TIME

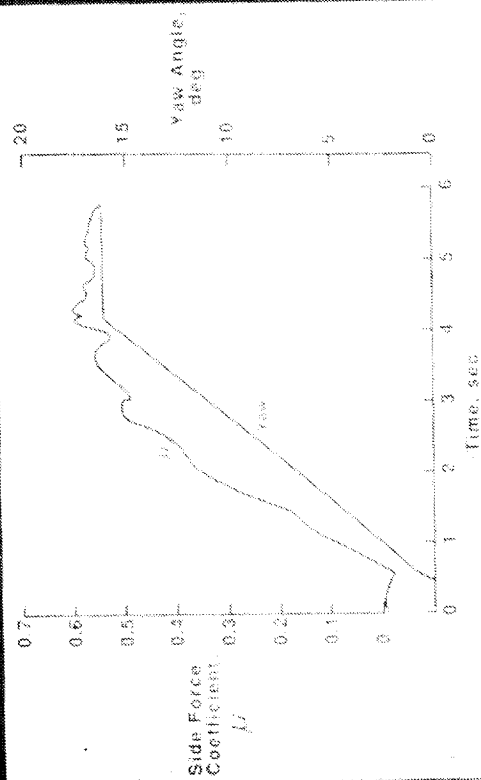
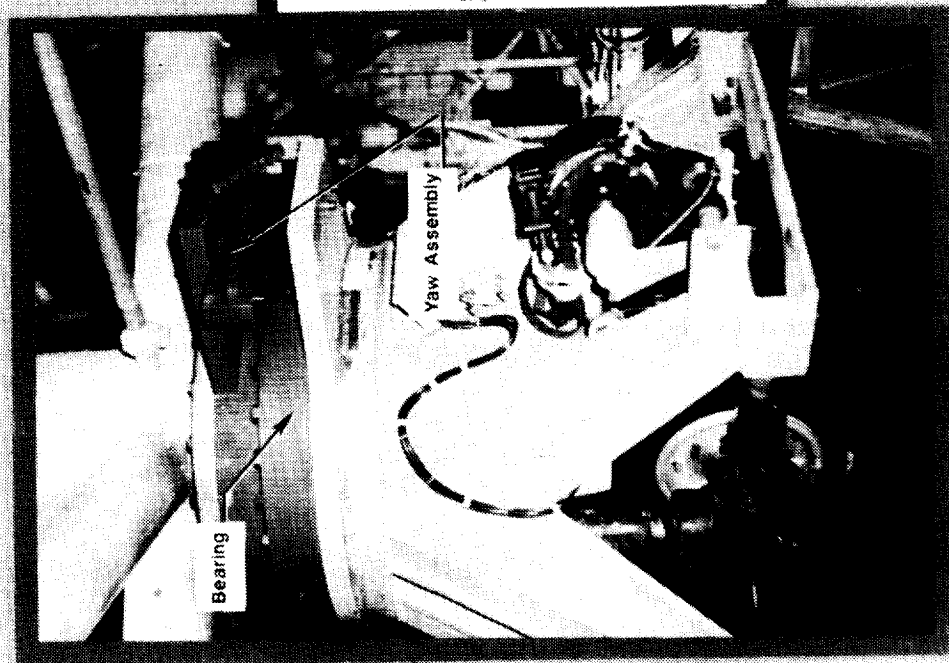


Figure 58 (b).

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## RUNWAY SURFACE TRACTION AND RADIAL TIRE PROGRAM

Sandy M. Stubbs, Pamela A. Davis, and Thomas J. Yager  
Landing and Impact Dynamics Branch

RTOP 505-63-01

**Research Objective:** The research objective is to study basic runway surface traction characteristics by using radial-belted, H-type, and bias-ply aircraft tires on different runway surface conditions, including surface grooving and environmental contaminants.

**Approach:** Three different tire types and three different tire sizes are being tested at the Aircraft Landing Dynamics Facility (ALDF). These tires are being tested at various speeds on a smooth ungrooved concrete runway under dry and wet surface conditions. Load-deflection, braking and cornering tests are being conducted to define the mechanical properties and friction characteristics of the different tire types and sizes.

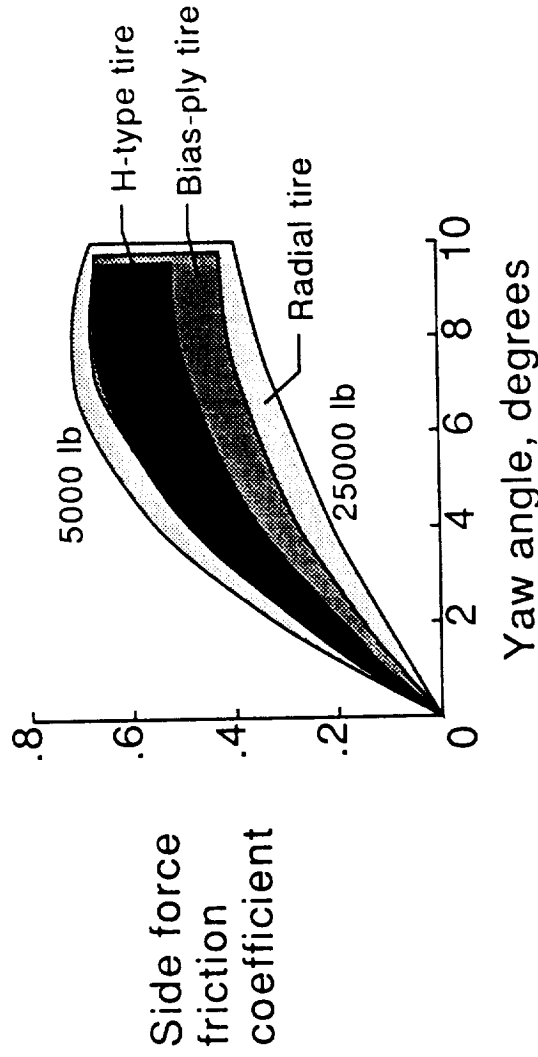
**Accomplishment Description:** The 40 X 14 and 26 X 6.6 size tires have been tested at the ALDF. The 40 X 14 tire, which is a main-gear tire on aircraft such as the Boeing B-737 and the McDonnell-Douglas DC-9, was tested in a bias-ply, radial-belted and H-type bias-ply design. Static load-deflection tests, braking tests, and cornering tests were conducted. The cornering characteristics of this size tire on a dry runway at 100 knots are shown in the attached figure for a range of vertical loads. The variation of vertical load affects the cornering characteristics of the radial tire to a greater extent than the cornering behavior of bias-ply or H-type tires. These results indicate that the ground handling properties of aircraft equipped with radial tires may be more sensitive to aircraft weight variations than aircraft equipped with bias-ply or H-type tires. The 26 X 6.6 tire size, which is the nose-gear tire for the McDonnell-Douglas MD-80, has been tested in a bias-ply and radial-belted design. The cornering results for these tires are shown in the second figure. At the lower yaw angles, the radial tire cornering behavior is effected less by vertical load variations than the cornering behavior of the bias-ply tire. In general, however, the 26 X 6.6 radial and bias-ply tires have comparable cornering properties.

**Significance:** The information shown in the attached figures will help to establish a national database for radial-belted and H-type aircraft tires that will be used to compare their mechanical property and friction characteristics with those of bias-ply tires. These data will also enhance aircraft safety during ground operations under adverse weather conditions.

**Future Plans:** Future tests will be conducted with a third tire size on an ungrooved runway. All three tire sizes will be tested on various grooved concrete runways in order to establish the effect of pavement texture variations on tire performance. This information will be documented in a reference publication to be used as a landing gear design guide.

Figure 59 (a).

# **START PROGRAM DEFINES CORNERING PROPERTIES OF BIAS-PLY, H-TYPE, AND RADIAL AIRCRAFT TIRES** 40 X 14 tires, 100 kts, Smooth dry concrete

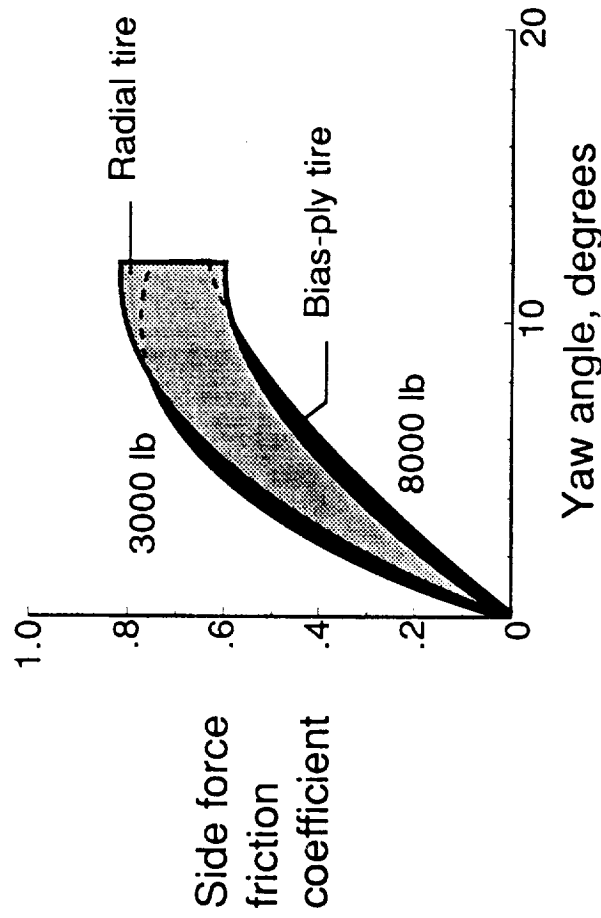


- Peak cornering friction between 7 and 9 degrees
- Magnitude of side force friction coefficient decreases with increasing vertical load
- Greatest effect of vertical load variations on radial tire and least effect on H-type tire
- Ground handling properties of aircraft equipped with radial tires may vary between heavy-weight takeoffs and light-weight landings

Figure 59 (b).

# **START PROGRAM DEFINES CORNERING PROPERTIES OF BIAS-PLY AND RADIAL AIRCRAFT TIRES**

26 X 6.6 tires, 100 kts, Smooth dry concrete



- Peak cornering friction between 10 and 12 degrees
- Magnitude of side force friction coefficient decreases with increasing vertical load
  - At lower yaw angles, the radial tire is effected less by vertical load variations than the bias-ply tire
  - Cornering properties are comparable

Figure 59 (c).

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# SPACECRAFT DYNAMICS RESEARCH

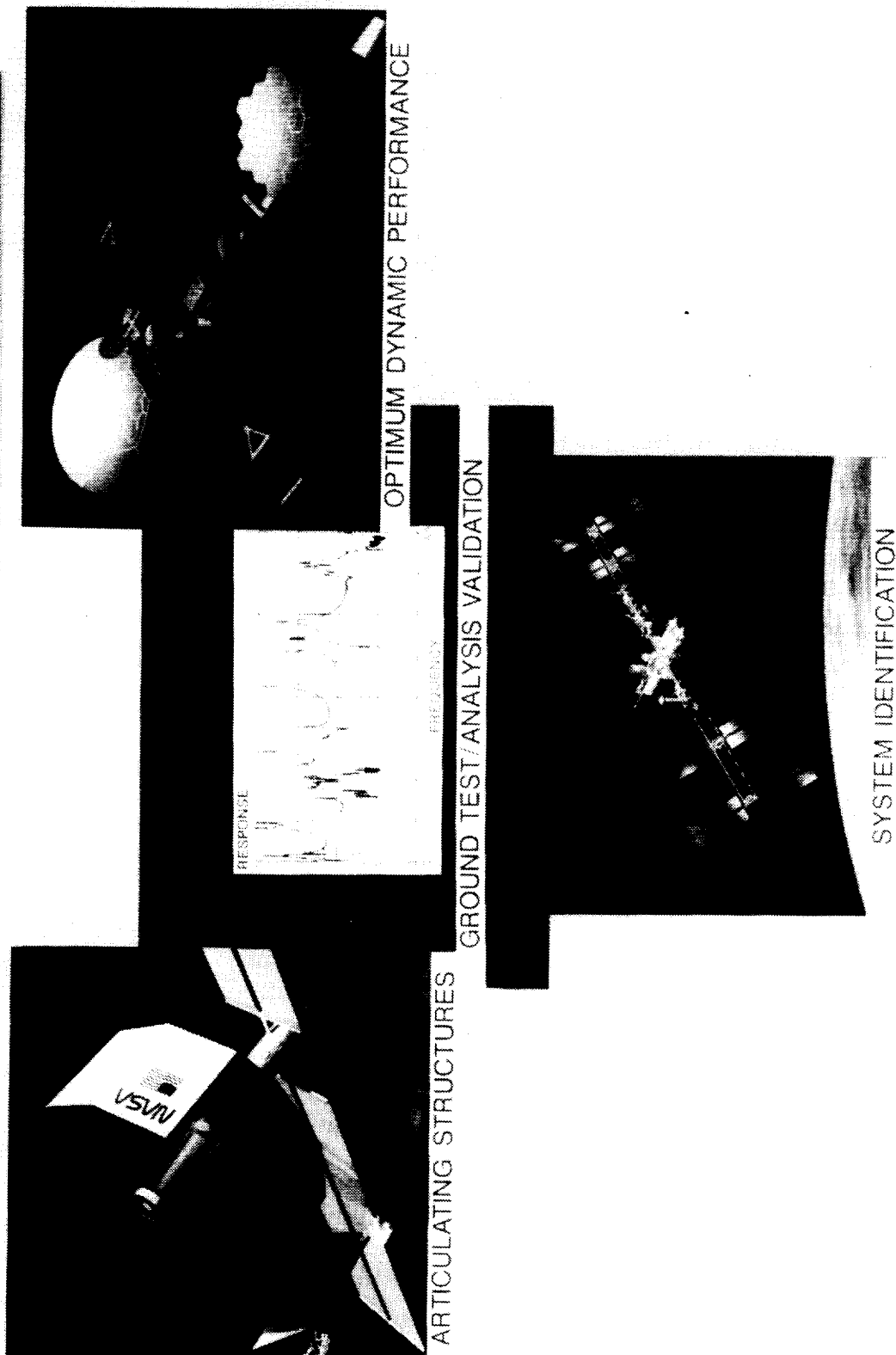


Figure 60.

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# SPACECRAFT DYNAMICS FUTURE PLANS (FY 91-95)

**GOAL**

DEVELOP CSI GROUND TEST TECHNOLOGY

**KEY OBJECTIVES**

- IDENTIFY TECHNOLOGY ISSUES USING GROUND BASED TESTBEDS



- VALIDATE MODERN CONTROL THEORY FOR SPACE APPLICATIONS

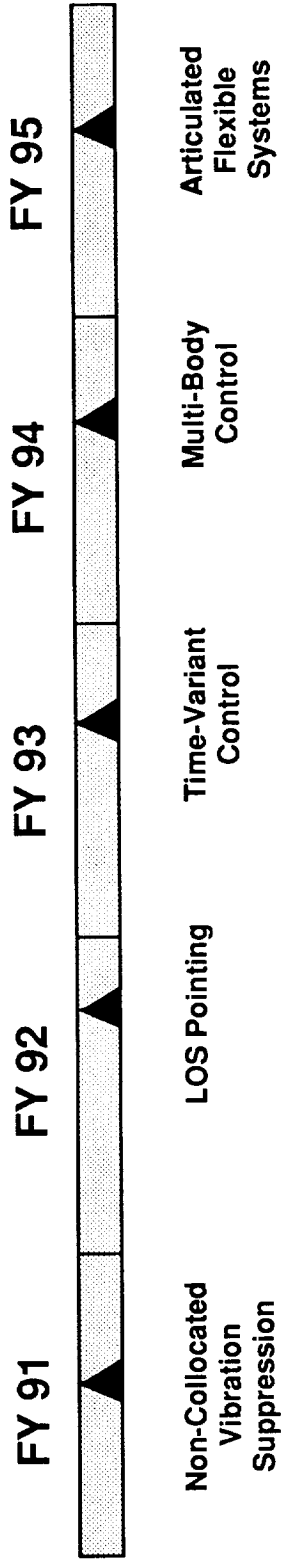


Figure 61 (a).

# SPACECRAFT DYNAMICS FUTURE PLANS (FY 91-95)

**GOAL**  
 DEVELOP VALIDATED SCALE MODEL TECHNOLOGY FOR ON-ORBIT  
 RESPONSE PREDICTION OF LARGE SPACE STRUCTURES

**KEY OBJECTIVES**

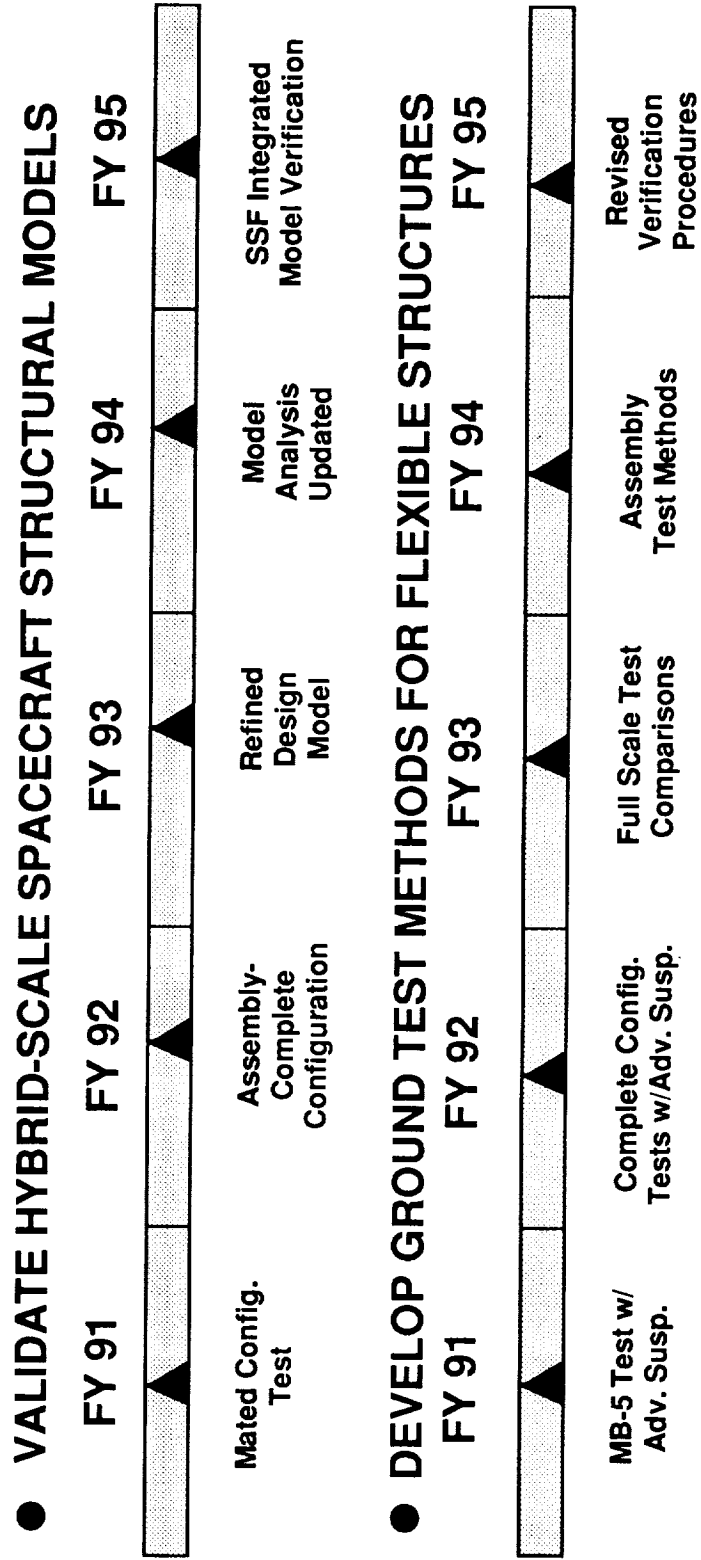


Figure 61 (b).



# SPACECRAFT DYNAMICS FUTURE PLANS (FY 91-95)

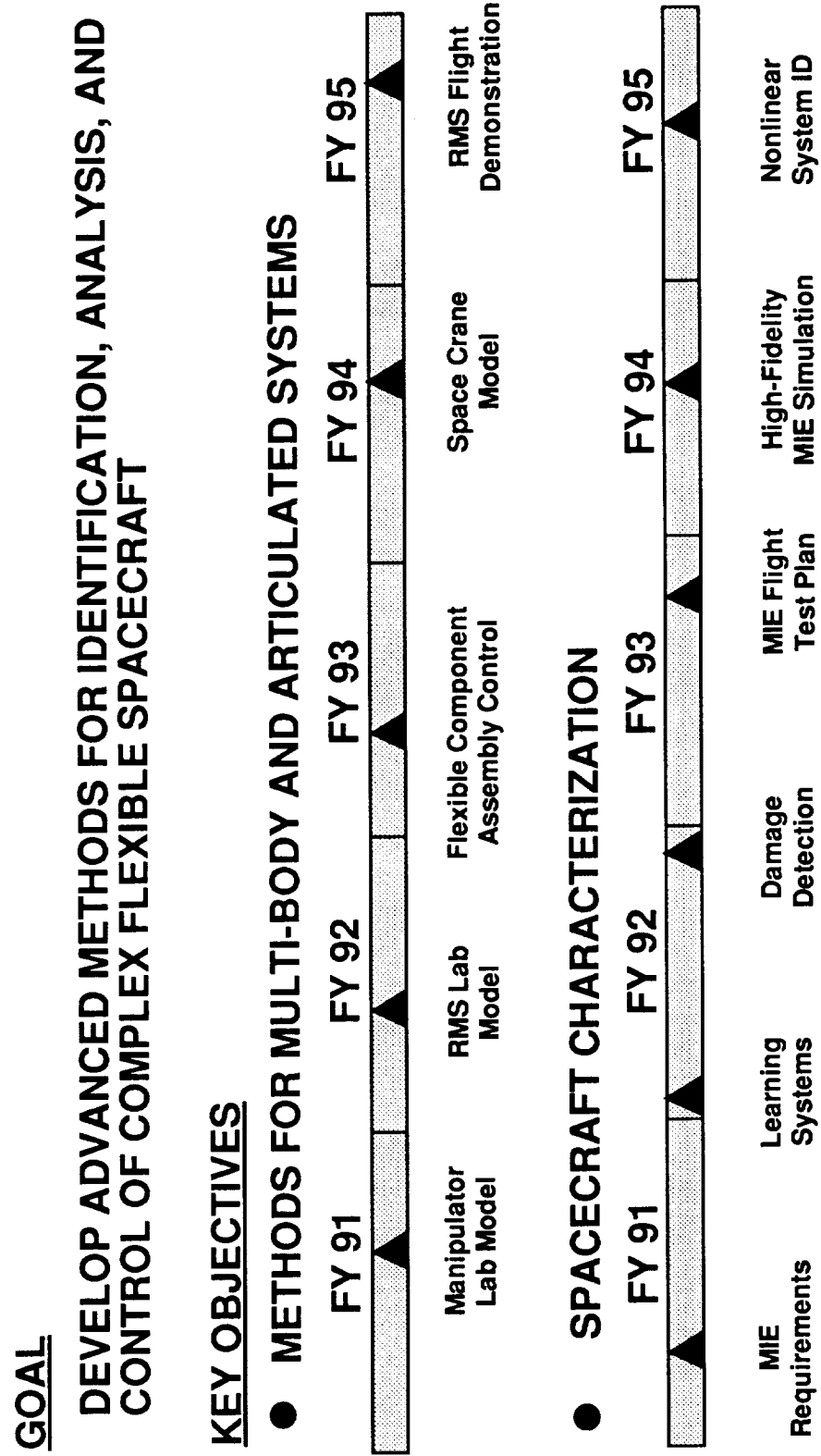


Figure 61 (c).

## CONTROL OF FLEXIBLE MINI-MAST DEMONSTRATED BY CSI INVESTIGATORS

S.E. Tanner, L. G. Horta, and Z.C. Kim (Lockheed)  
Spacecraft Dynamics Branch

RTOP 590-14-61

**Research Objective:** The objective of this research, conducted under the Controls-Structures Interaction (CSI) Guest Investigator (GI) Program, is to verify, on realistic hardware, candidate control laws for flexible spacecraft active vibration control. The performance of future large spacecraft can be significantly enhanced if proposed methods can be applied for using on-board vibration measurement to drive actuators which oppose or dissipate the vibration.

**Approach:** This research is conducted on a 20-meter-long, 1.2-meter triangular cross-section, deployable, flight-quality truss, known as the Mini-Mast and sketched on the left in the accompanying figure. The structure, mounted vertically and cantilevered at the base, is controlled by three torque wheels mounted orthogonally at the tip and controlled by a real-time digital computer using vibration measurements fed back from on-board sensors. A variety of position, rate, and acceleration sensors are available. Potential investigators are supplied with a mathematical model of the complete system which has been extensively verified by in-house dynamic tests. In addition, investigators are offered the opportunity to participate in dynamic tests to identify their own mathematical model of the system. Using their chosen model, investigators design control laws to satisfy their particular research objectives and submit them to Langley for safety verification (i.e., assurance of stable, non-destructive behavior) on a computer simulation of the system. Once verified in simulation, the control laws are implemented in laboratory tests with the researcher participating. Investigators include both in-house researchers and eight Guest Investigators from academe and industry who were selected in open competition.

**Accomplishment Description:** More than 15 digital control laws, designed by both NASA and GI researchers have been subjected to simulation. The behavior of the integrated system with each controller was examined, and predicted responses were compared with actual responses. On the right-hand side of the accompanying chart, simulated and measured results from two control investigations by university GIs are shown, along with the simulated open-loop behavior (no feedback control). Investigator #1 used measurements of position relative to ground in his design. Investigator #2 used only acceleration and rate sensors as these are more representative of measurements which will be available on orbit. Both investigators achieved good agreement between test and simulation. Both damping and modal frequencies of the Mini-Mast vary nonlinearly as a function of displacement amplitude. The experimental frequencies decrease as vibrations die out while the analytical frequencies remain unchanged throughout the simulation. In addition, the analytical model uses lower-than-measured modal damping values to ensure that the simulated response will provide a conservative "envelope of safety" around the actual response. Thus "good agreement" means that the simulation should predict the demonstrated larger amplitude and longer ring when compared to measured displacements from the testbed.

**Significance:** The successful implementation of active vibration control on a large flexible space-type structure has been demonstrated by several investigators. With adequately verified analytical models, the predictability of the results is high, indicating promise for the technology in improving dynamic performance in the design of future actual spacecraft.

**Future Plans:** Investigations of additional advanced control laws are expected to continue on the Mini-Mast testbed through early 1991.

Figure 62 (a).

# Control of Flexible Mini-Mast Demonstrated by Guest Investigators

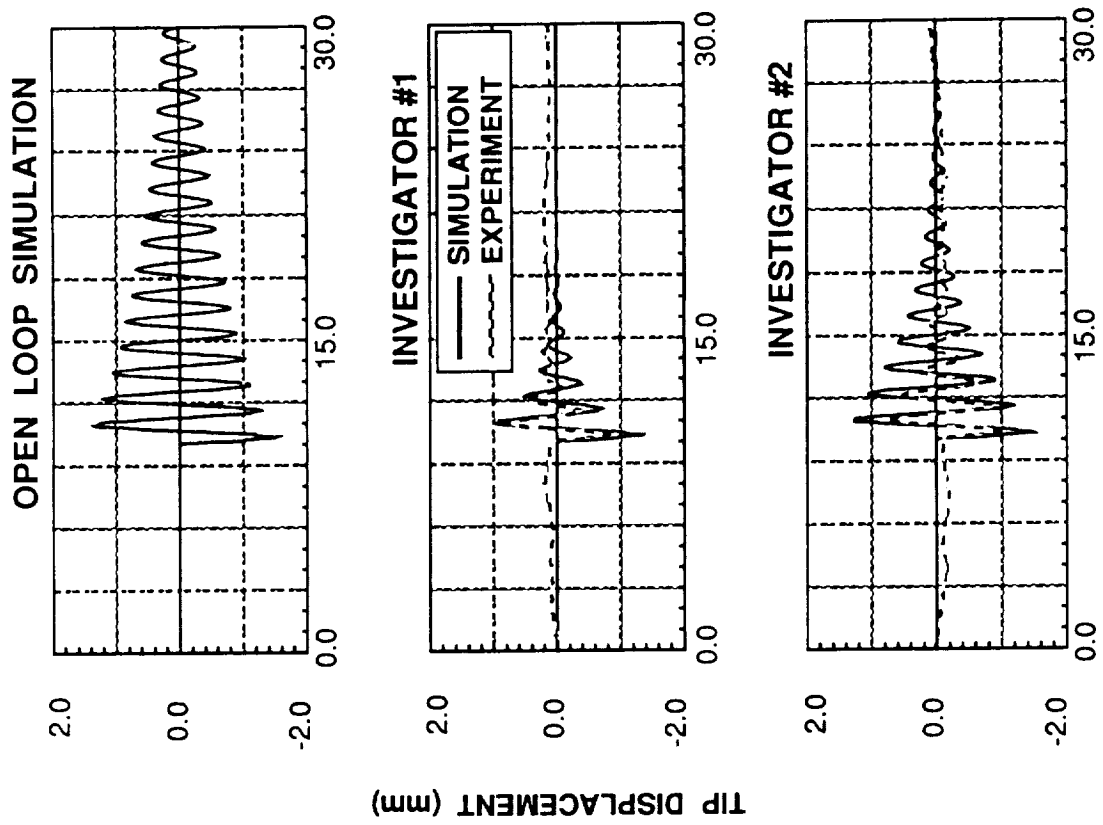
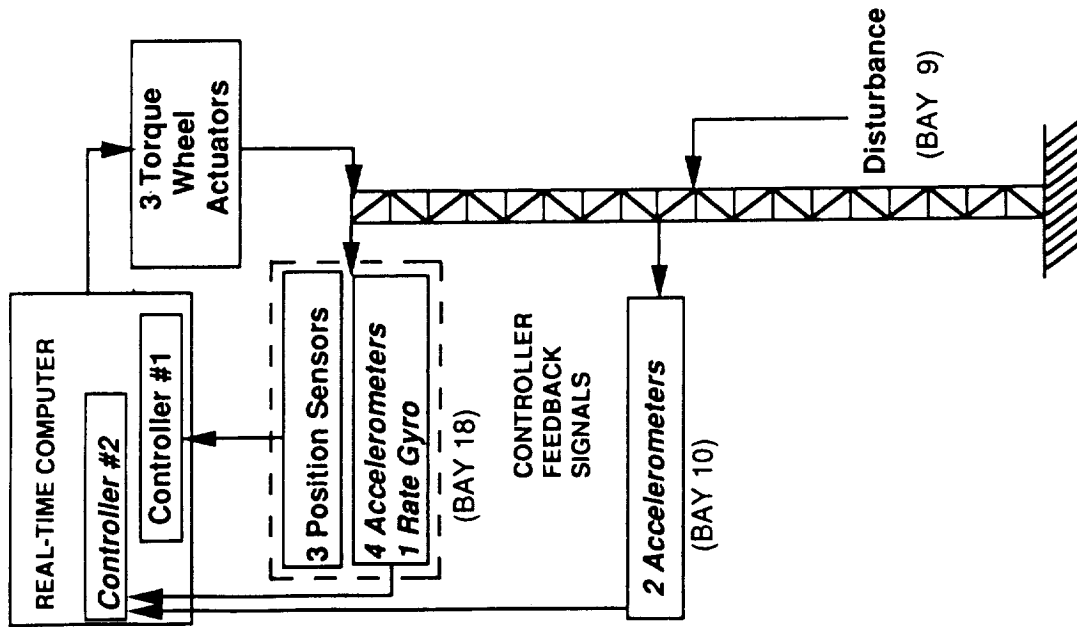


Figure 62 (b). TIME (seconds)

## CLOSED-LOOP CONTROL OF CSI EVOLUTIONARY MODEL TESTBED INITIATED

Lucas G. Horta, Anne Bruner (Lockheed), Jeff Sulla (Lockheed), Keith W. Belvin, Kenny Elliott and Jer-Nan Juang  
Spacecraft Dynamics Branch

RTOP 590-14-61

**Research Objectives:** A new testbed, the CSI Evolutionary Model, has been developed to experimentally evaluate approaches for the control of flexible spacecraft. Initial test objectives are to assess the adequacy of the test facility, to identify dynamic characteristics of the integrated system, and to investigate the performance of a non-model-based controller design.

**Approach:** A testbed configuration which simulates the control problems inherent in flexible, multi-component, science platforms was developed. The testbed structure is excited and/or controlled using on-board thrusters and its response is measured by accelerometers. Initially, the system is vibrated using the thrusters and the resulting free response data is analyzed to obtain frequency and damping estimates. When characteristics of the system are understood, feedback control is implemented using the accelerometer signals to drive the thrusters in a manner which augments the structural damping.

**Accomplishments:** The model, shown in the photograph, has five major structural components, a 52.5-foot center truss, a 16-foot diameter reflector, a 9.2-foot tower which supports a laser, and two 16.7-foot cross-member trusses. The system is supported by a steel cable harness attached from the cross members to the ceiling. The actuators are proportional airjet thrusters using a 125 psi external air supply. A total of 8 actuator pairs, producing 4.4 lbs thrust per pair, are placed at four locations along the truss. In addition, 8 accelerometers are collocated with the thrusters for identification and control experiments. A collocated-sensor-actuator feedback control law was designed which used the measured accelerations in enhancing the damping of the low frequency modes. The plots on the right show the test results for a typical experiment scenario. The structure is excited at the center using two thrusters in the y and z directions (shown by arrows) and the acceleration in the y direction is measured at the lower right corner. Each sensor output signal is multiplied by a scalar gain factor which varies from 0.0 to 1.0 and is used to avoid excessive response during initial tests of control laws. The top chart shows a 20-second sinusoidal excitation of the first two bending modes followed by a 20-second open-loop response (gain factor = 0.0). The estimated open-loop modal damping ratio is approximately 1.9 percent of critical. The middle plot shows the closed-loop results using a gain factor of 1.0 after the initial excitation. The design goal is to augment damping of the first bending modes. For those modes, damping is increased to 12.8 percent but an instability of a high frequency mode occurs at approximately 7.5 Hz. The instability occurs because of the sample delay introduced by the digital controller. When the gain factor is decreased to 0.5, closed-loop damping is reduced to 3.8 percent but the instability no longer occurs.

**Significance:** The initial closed-loop testing has demonstrated the operational readiness of the test structure, verifying the truss dynamics and suspension, data acquisition system, and real-time control links.

**Future Plans:** Thorough system identification testing will be conducted to further refine the analytical models of the system. Then, the testbed will be used by in-house and guest investigators to validate and test advanced control law design methods for large space structures. The testbed configuration will evolve over a multi-year period to allow investigation of increasingly complex problems.

Figure 63 (a).

# CLOSED-LOOP CONTROL OF CSI EVOLUTIONARY MODEL TESTBED INITIATED

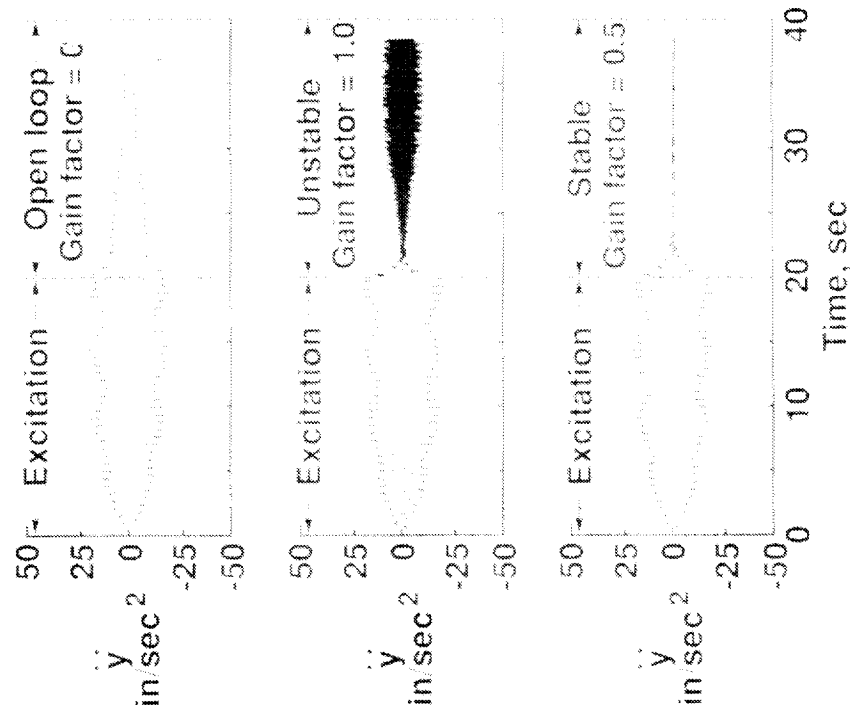
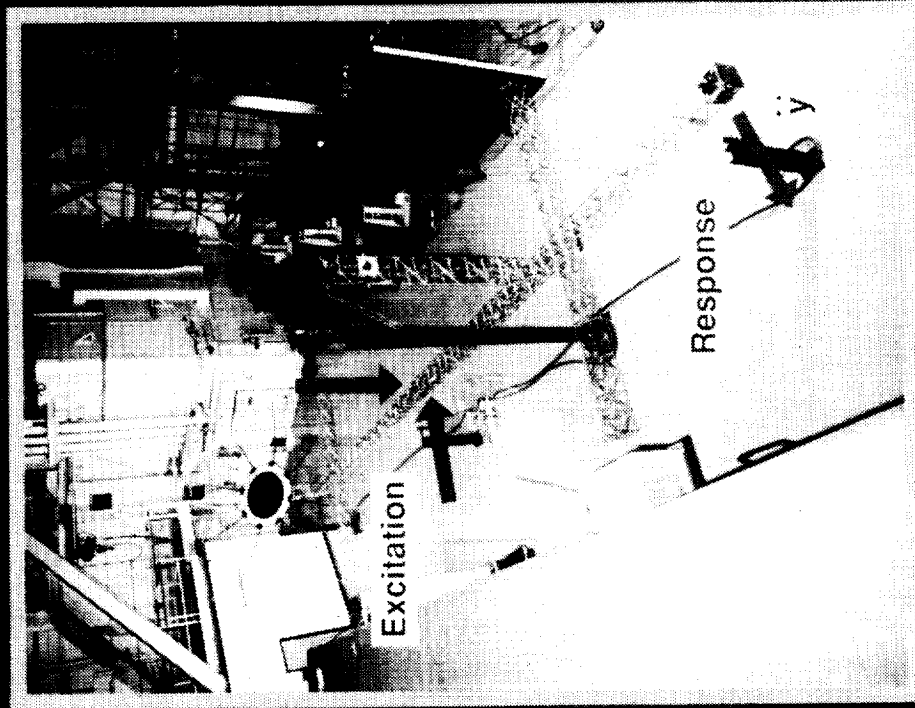


Figure 63 (b).

## DISCRETE LQG CONTROLLER DESIGN FOR A 10-BAY TRUSS MODEL

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RTOP 590-14-21

**Research Objective:** Demonstrate the application of discrete LQG controller designs for vibration suppression to a 10-bay truss test article and validate a design model of the structure. The design model is obtained from experimental data by using a system identification technique recently developed in the Spacecraft Dynamics Branch.

**Approach:** A vertically cantilevered 10-bay test article has been assembled including two independent compressed air proportional thrusters and two accelerometers mounted orthogonally on the tip of the truss beam. The 10-bay truss was first driven by the two thrusters using a single sinusoidal input and the test data measured from the accelerometers were then used to identify a state-space model of the structure by applying the recently developed algorithm. The sinusoidal input is, in general, not sufficiently rich for complete model identification. However, the algorithm successfully identifies a reduced model that best fits the limited length of data. Given the identified discrete input-output model of the 10 bay test article, MATLAB software routines were used to solve the discrete-time LQG regulator/estimator problems. The controller obtained was then simulated using the design model and implemented on the actual test article.

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**Accomplishment Description:** A discrete LQG controller was designed and tested on the 10 bay test article. The two independent compressed air proportional thrusters were used to apply control forces to the free end of the truss with the accelerometers as feedback sensors. A VAX 3200 computer was interfaced with the CAMAC data acquisition system to provide a digital control capability. Open loop testing was performed to obtain system identification data. With the analytical design model obtained from open loop testing, the discrete LQG design process was used to obtain a digital controller to provide vibration suppression to the 10-bay truss. This controller was implemented in real-time at a 150 Hz sample rate. The attached chart shows the 10-bay test configuration and an overlay of a typical simulated and experimental accelerometer output, error between actual and simulated acceleration data, and thruster command data. The correlation between experimental and simulated results is indicated by the low acceleration error data.

**Significance:** Given a high fidelity model of the structure, this research demonstrated the use of a discrete LQG controller to provide vibration suppression for the 10-bay truss. The excellent predictive performance of this test demonstrated the high fidelity of the design model identified from test data by using the identification algorithm developed in the Spacecraft Dynamics Branch.

**Future Plans:** Using the CSI Evolutionary Model, a test article which is representative of future large Earth Observing satellites, the system identification and digital control law design methodology will be applied to assess performance in more realistic applications.

Figure 64 (a).

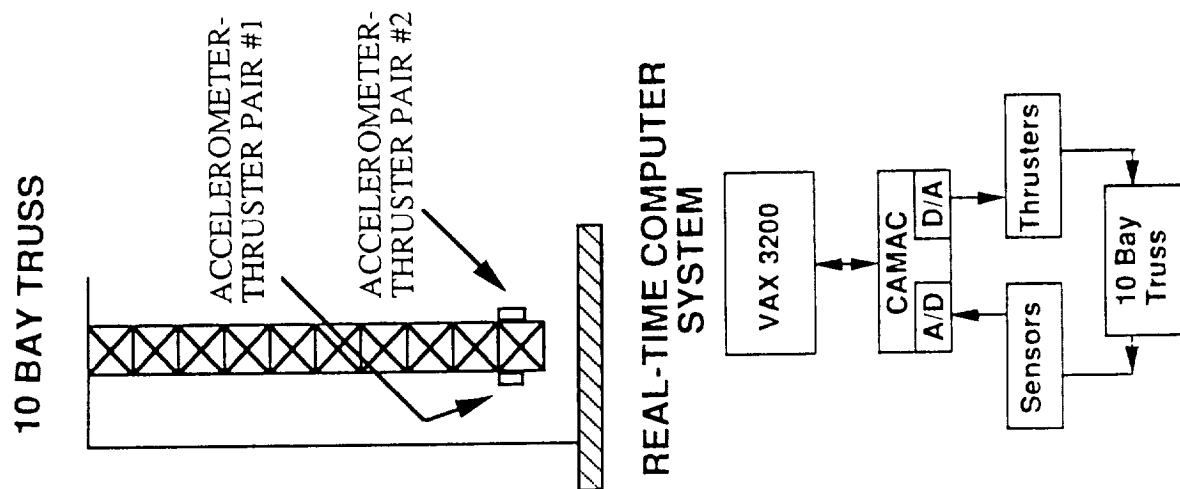
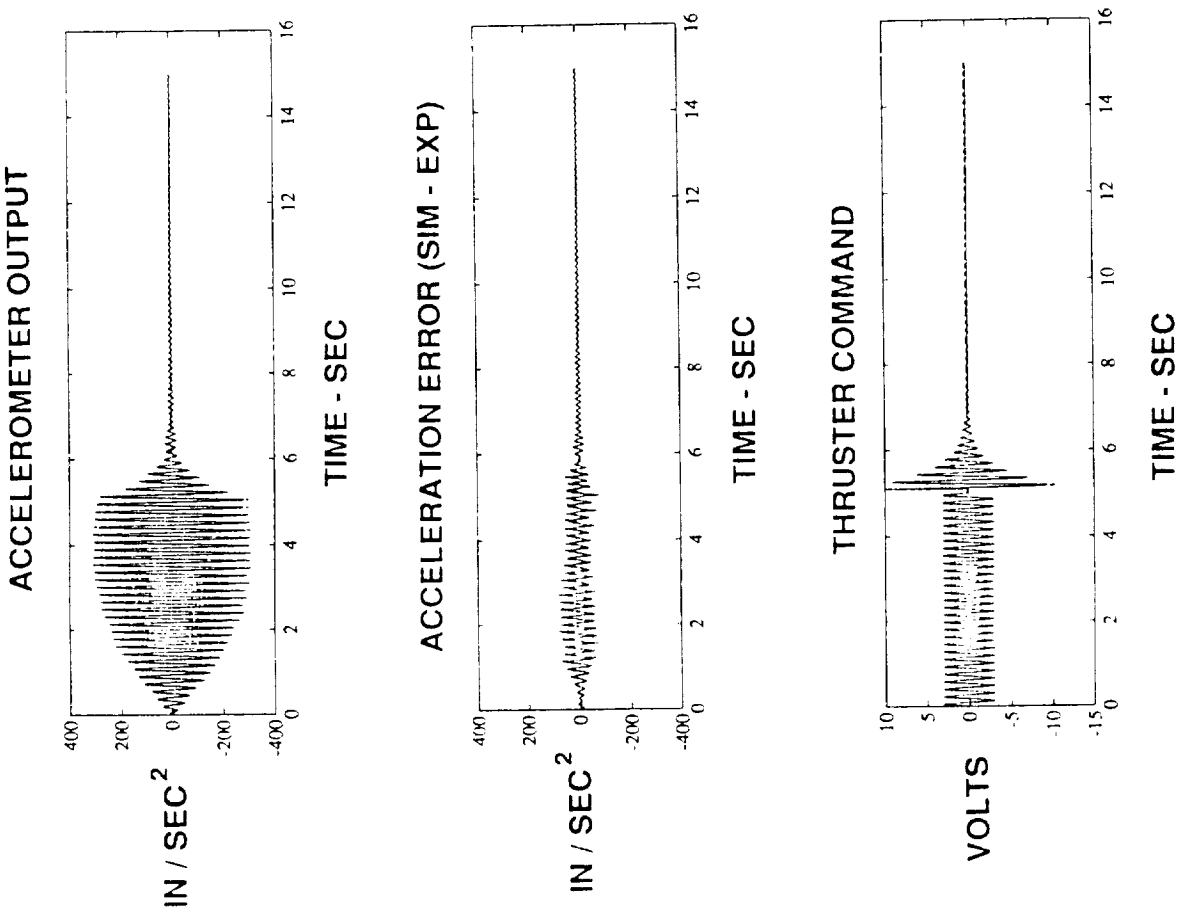


Figure 64 (b).

## CONTROL SYSTEM FAILURE DETECTION

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RTOP 590-14-61

**Research Objective:** Future large space structures will require control systems which will be comprised of many actuator and sensor components. With so many components operating for long periods without maintenance support, failure of some of these components during the mission lives of space structures will be inevitable. Thus, to ensure the operational effectiveness of such structures, some method(s) of fault detection and component redundancy must be developed. The objective of this research is to study methods of failure detection of sensor and actuator components using experimental data.

**Approach:** Two failure detection algorithms were developed and were applied to experimental data taken from the Mini-Mast Testbed. The sensor outputs and random torque wheel commands data were used in off-line simulations of the two failure detection algorithms. To create actuator failures, for each run, one wheel was disconnected during the test for a short period. Sensor failures were created by modifying the selected sensor signal(s) (to achieve the desired 'failure(s)') prior to applying the two algorithms. Both algorithms were based on general parity relations: residual values were computed from the differences between the experimental sensor output data and the modeled sensor output data, the variations of these residuals over time were then used as indications of failures. The figure on the left shows a general flowchart of failure detection with parity relations. The first algorithm used model based parity relations (based on an existing 5 state modal model) and the second used identified parity relations (involving 10th order input/output models, which were computed from test data using least squares). Both algorithms were evaluated under actuator failures (i.e., zero input), as well as different simulated sensor failure modes (zero output, half wave rectification, added noise, bias shift and multiplicative gain error) and under different digital sampling periods. Also examined, for the identified parity relations algorithm, were the differences between single sensor parity relations (i.e., using only data from one sensor) and double sensor parity relations (i.e., using data from two sensors).

**Accomplishments Description:** Sample computed residuals, taken from a single sensor parity relations simulation, are shown on the right. The large jumps in the residuals indicate the simulated off failure of a sensor. Initial results have shown that the parity relations technique can give indications of all the simulated sensor failures, with the sole exception of bias shift. Some failures, however, did not show up in the computed residuals very clearly, and thus they probably could not have been detected by automated software. Actuator failures, however, could not be determined. Other findings have shown that the identified parity relations algorithm performed better than the model based algorithm, and that double sensor parity relations were more reliable than the single sensor parity relations. Finally, it was found that longer sampling rates gave better results.

**Significance:** Actuator and sensor failure detection algorithms have been developed which initially show good performance over a range of failure modes. Refined versions of these algorithms can be very useful, if not essential, to the operational success of future space systems which rely on many actuator and sensor components.

**Future Plans:** These include further development of the general parity relations method, with emphasis on more robustness to modeling errors, trying to identify actuator failures, studying a failure detection filter for use in closed loop tests, and writing a fault detection software package for general use on the Mini-Mast Testbed.

Figure 65 (a).



# CONTROL SYSTEM FAILURE DETECTION DEMONSTRATED ON MINI-MAST

## FAULT DETECTION METHOD

- U(k) - ACTUATOR COMMAND
- Y(k) - MEASURED SENSOR
- $\alpha, \beta$  - MODEL COEFFICIENTS
- k - SAMPLE POINT
- N - SYSTEM ORDER

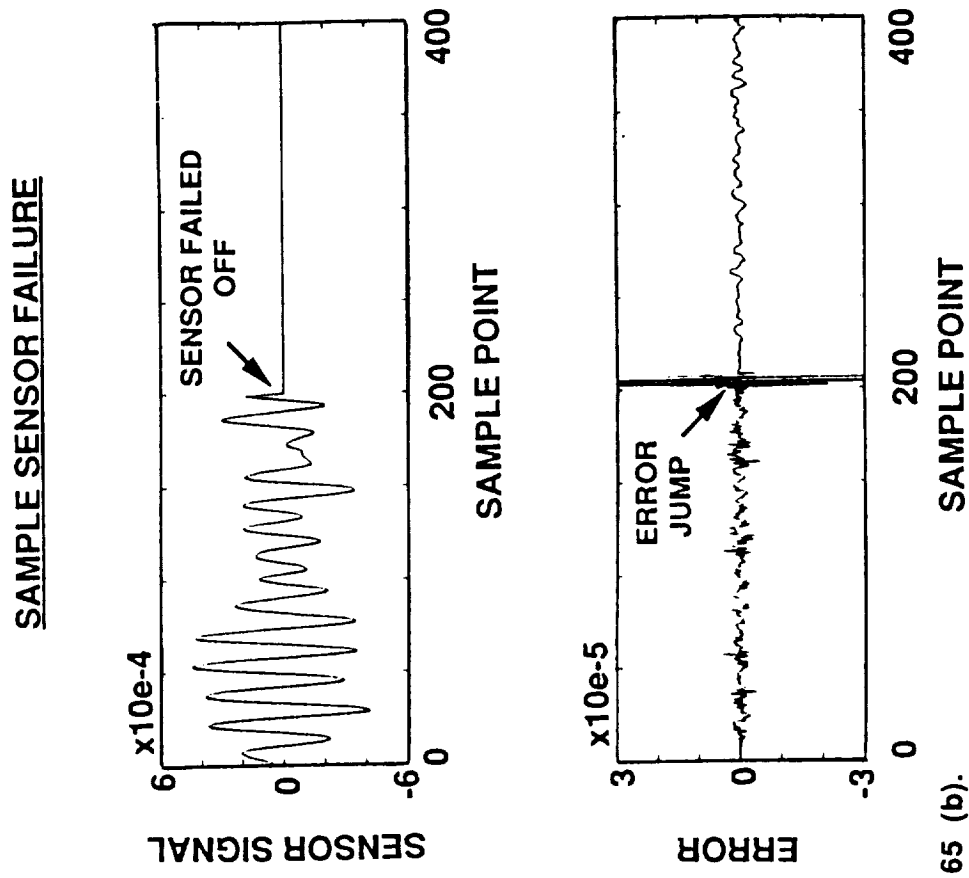
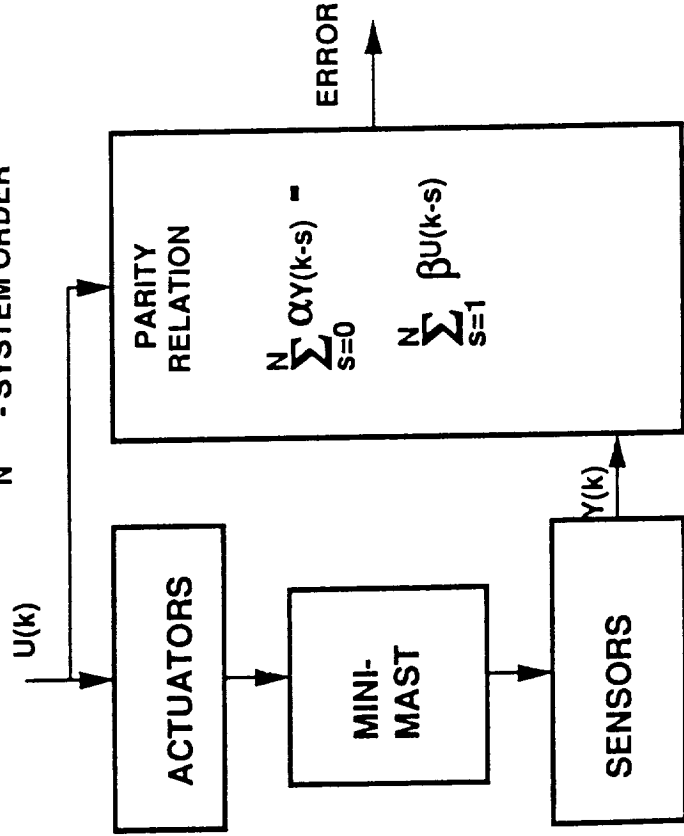


Figure 65 (b).

## DSMT HYBRID-SCALE MODEL FABRICATED FOR EARLY CONFIGURATION ASSEMBLY TESTS

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Spacecraft Dynamics Branch & Lockheed Missiles and Space Co.

RTOP 590-14-31

**Research Objective:** The objective of this research is to provide an experimental capability for investigating the use of scale models of large spacecraft structures in ground tests to improve pre-flight analytical predictions and establish sensitivities of structural response.

**Approach:** A hybrid-scale structural dynamics model representing Space Station Freedom has been developed and fabricated under contract by the Lockheed Missiles and Space Co. Hybrid scaling laws were developed to provide a means for designing scale models of very large structures which perform realistically while retaining practical dimensions. These laws were applied to the design of the Space Station Freedom structure. The resulting model is denoted a 1/5 : 1/10 scale model since it employs a 1/10-size truss structure comprised of 1/5-scale truss joints and mass properties to yield a model with global properties of a 1/5-scale dynamic model.

**Accomplishment Description:** Model hardware to assemble up to an MB-5 station configuration has been fabricated. All major station structural components were included in the design. Some components were simulated (e.g., module-to-truss interconnects) due to insufficient full-scale design information. Because of the evolutionary nature of the station, the model components were designed for modular attachment to the truss and easy reconfiguration. The model provides a ground test article with challenging dynamic characteristics including closely spaced and low-frequency vibration modes and potential interactions between flexible components and global truss vibrations. Shown in the figure is an MB-2 configuration suspended from cables for dynamic tests. This configuration was selected as the first structure for comparing predictions from component level synthesized data with that obtained from fully integrated testing.

**Significance:** This scale model represents a unique opportunity to obtain early ground test data from a complex, three-dimensional space structure. Also, the limitations of hybrid-scale models for predicting the response of full-scale spacecraft will be established. Furthermore, lessons learned from this program will provide valuable information to the full-scale station program as it enters the Phase C/D phase.

**Future Plans:** The MB-5 configuration, which includes the addition of a module and resource node, has been selected as the next major test article. A fabrication contract is in place to provide the remaining modules for the assembly complete module cluster. Following completion of the MB-5 tests, the assembly complete (MB-15) configuration will be assembled.

Figure 66 (a).

# DSMT HYBRID-SCALE (HMB-2) MODEL

EPS RADIATOR

BETA-JOINT

SOLAR ARRAY

TCS RADIATOR

SUSPENSION CABLE/LOAD CELL

RCS PALLET

TRUSS STRUCTURE

Figure 66 (b).

# ANALYTICAL SIMULATION CONFIRMS FEASIBILITY OF SPACE STATION MODAL IDENTIFICATION EXPERIMENT

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RTOP 590-14-31

**Research Objective:** The Modal Identification Experiment (MIE) provides a unique opportunity to perform a series of on-orbit modal tests for Space Station Freedom (SSF) and its intermediate flight configurations. The objective of this research is to perform a complete end-to-end on-orbit modal testing simulation using an early flight configuration in order to assess the feasibility of the experiment.

**Approach:** A finite element model of an early flight configuration was developed and the undamped structural modes below 5 Hz were identified. Jet firings of the Reaction Control System (RCS) consistent with a maneuver for reboost were employed to examine structural responses at the various points of interest in the structure to define a set of target modes for modal testing. Nineteen target modes were selected which together account for 95% of the global acceleration response of the structure in a modal analysis. A set of 43 accelerometers was placed on the structure to measure the response. The Eigensolution Realization Algorithm (ERA) was employed to extract the modes from the measured acceleration.

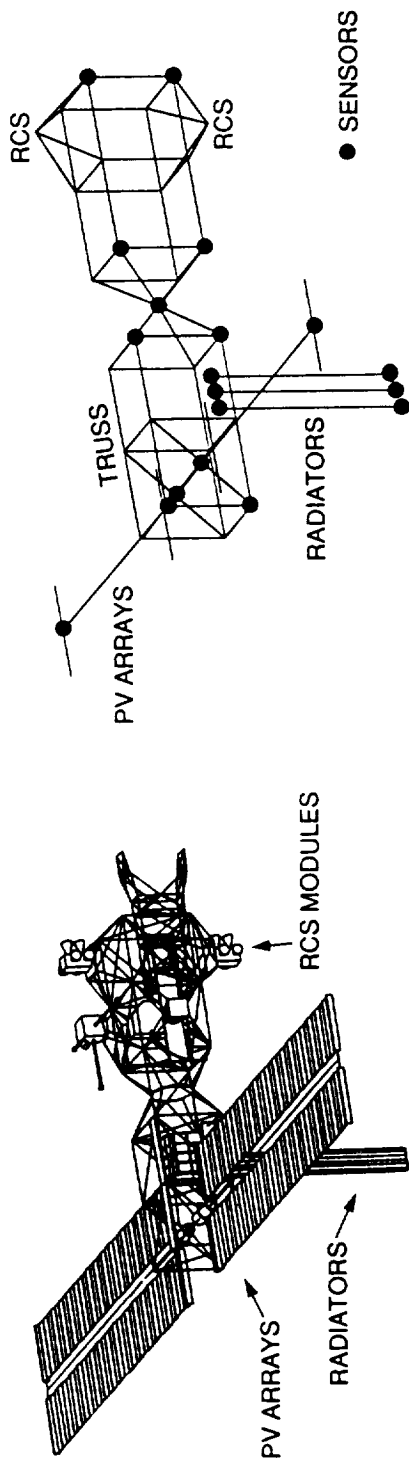
**Accomplishment Description:** Simulation results indicated that on-orbit modal testing using RCS jets as an excitation device and accelerometers as sensors would be successful in identifying the target modes even with noise in the measurement. Without measurement noise, 52 modes including all 19 target modes were identified. When white noise levels of 0.56% and 2.8% noise to signal ratio were added to the measurement, 20 and 17 modes were recovered, respectively. One target mode could not be identified with the lower noise level and 3 target modes with the higher noise level.

**Significance:** Techniques necessary for on-orbit modal testing simulation such as finite element model development, excitation definition, target mode selection, and modal parameter recovery algorithm performance have been examined through an end-to-end modal testing simulation of a Space Station Freedom early flight configuration. The simulation results confirm that the on-orbit MIE is feasible.

**Future Plans:** Using an analytical test model based on intermediate SSF configurations and the assembly complete SSF, complete end-to-end on-orbit modal testing simulations from structural modeling to modal parameter identification will be performed. The influence on accuracy of modal recovery of expected disturbances such as the active attitude control and momentum management systems and the nonstationary aspects of the SSF configuration will be investigated.

Figure 67 (a).

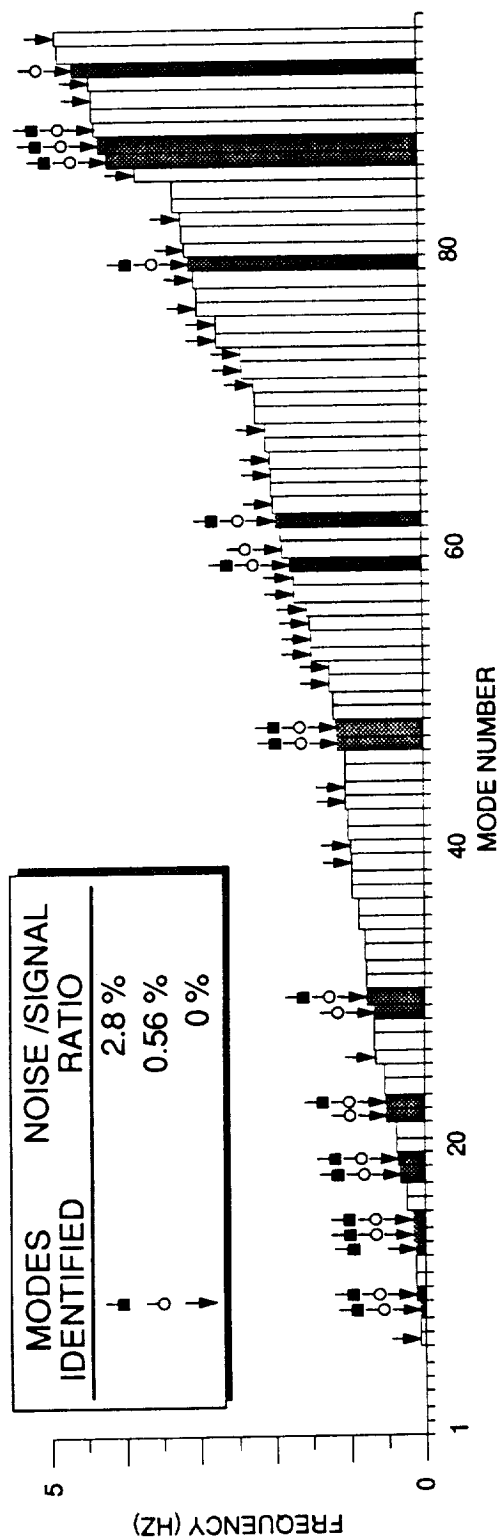
# ANALYTICAL SIMULATION CONFIRMS FEASIBILITY OF SPACE STATION MODAL IDENTIFICATION EXPERIMENT



EARLY FLIGHT CONFIGURATION

ANALYTICAL MODEL WITH 43 SENSORS

TARGET MODES WHICH CONTAIN 95% OF ELASTIC RESPONSE BELOW 5 HZ TO RCS JET FIRING



SIMULATION RESULTS

Figure 67 (b).

## LARGE SPACE STRUCTURES RESEARCH LABORATORY PLACED INTO OPERATION

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Spacecraft Dynamics Branch

RTOP 590-14-61 and 590-14-31

**Research Objective:** Future NASA space mission concepts currently envision very large, multi-function, multi-mission spacecraft capable of observing Earth's environment and supporting exploration of the Solar System. Many of the spacecraft will have multiple sensors and instruments with very precise pointing requirements, and/or requirements for very low disturbance levels due to other onboard activities. These requirements, when coupled with high performance, high gain control systems and very low structural mode frequencies due to spacecraft size and design, may lead to control-structure interactions which could seriously degrade the performance of the spacecraft. The objective of research in the Spacecraft Dynamics Branch is to understand the structural dynamic and control-structure interaction characteristics of large, flexible spacecraft.

**Approach:** Both analytical and experimental research is being conducted to define, develop, and validate structural dynamic and control-structure interaction analysis and testing methods. A key goal is experimental validation of the methods, using realistic scaled or full-size structural hardware, by comparison of measured response data with analytical results. To accomplish this goal, a new 5200 square foot laboratory facility has been brought on line for structural dynamics and controls testing. Initial test models include a 1/10 size scale model of Space Station Freedom (SSF), and a 55-foot long Controls-Structures Interaction Evolutionary Model (CEM).

**Accomplishment Description:** In early 1989, an approximately 80 by 80 by 80-foot high-bay area in Building 1293 became available for use by the Spacecraft Dynamics Branch for testing of large space structures. This area was emptied, cleaned and existing utilities, including the ventilation system and a 5000 psi air supply system, were reworked. A 10-ton work platform was designed, fabricated, and installed at the 73-foot to enable conventional cable suspension of models anywhere in the laboratory. A separate 60-foot high gantry was installed to isolate and suspend the 1/10 scale SSF model, and to support advanced suspension system device testing. Also installed were a 12-foot by 12-foot vertical backstop for cantilever structural testing, and an angle block and base plate for structural component testing. In order to conduct closed-loop control testing of the CEM, a trailer was positioned in the laboratory to serve as a control room. State-of-the-art data acquisition and control equipment was installed in the trailer, including a 128 channel GenRad/Cytec scanner system, a 16 channel Zonic modal test system, and a 36-input, 36-output CAMAC analog/digital and digital/analog conversion system. A fiber optic link from the CAMAC system to a remotely located real-time control computer was established for testing of digital control laws on the CEM. Both initial models have been suspended and installed in the laboratory, and have been used for research testing since May of 1990.

**Significance:** A unique ground-based facility for testing of large spacecraft systems has been brought online. The facility provides the space necessary for simultaneous testing of large structural test articles over long periods of time, and it provides state-of-the-art data acquisition and control equipment for control-structure interaction testing and development of ground-based and on-orbit modal test methodologies.

**Future Plans:** During 1991, the facility will be further modified to provide a permanent control room, to provide better access to the 73-foot high work platform, and to improve auxiliary utilities. Longer term plans call for doubling the high bay area.

Figure 68 (a).

LARGE SPACE STRUCTURES RESEARCH  
LABORATORY PLACED INTO OPERATION

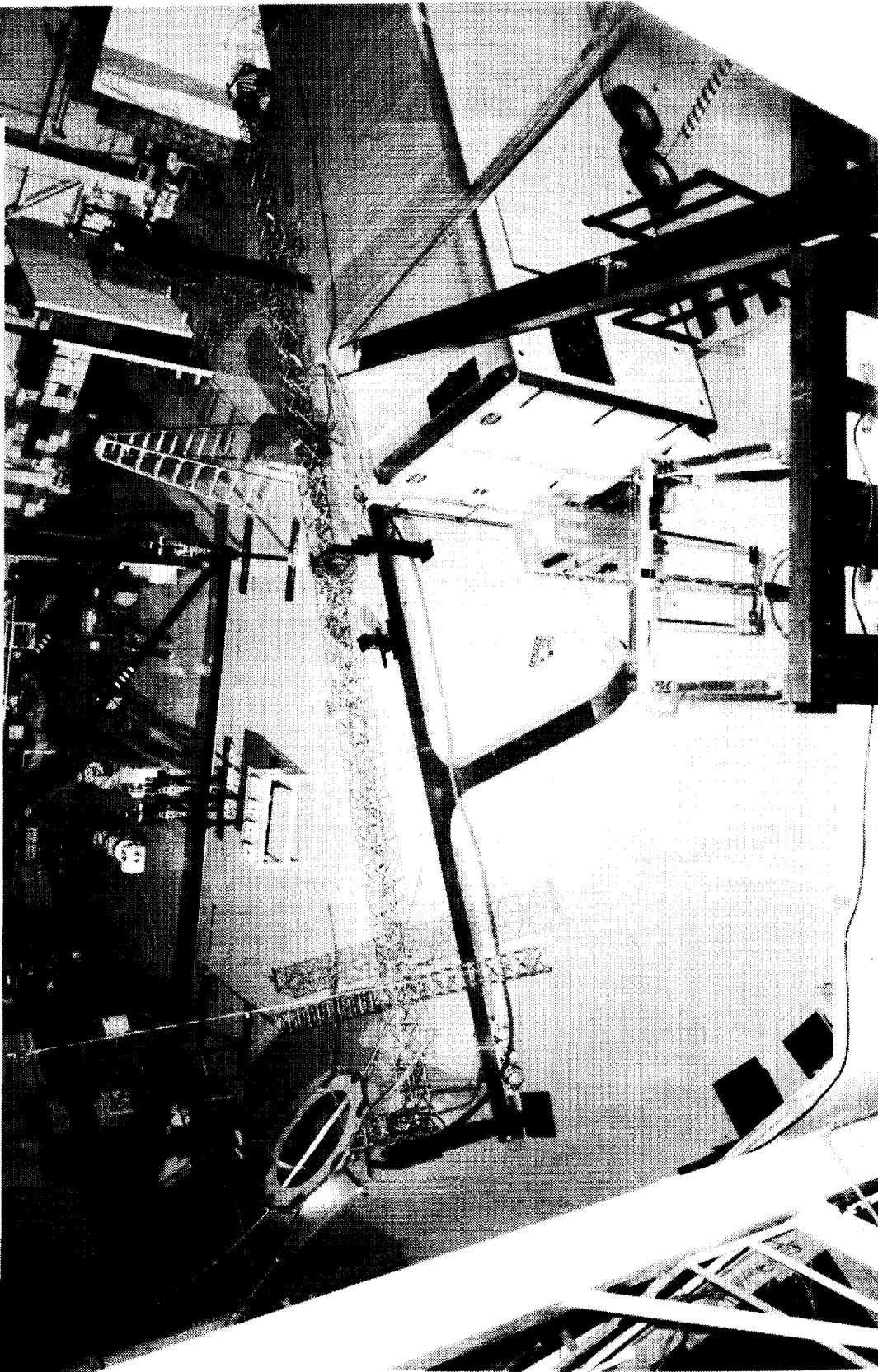


Figure 68 (b).

# A NEW RECURSIVE SYSTEM IDENTIFICATION METHOD DEVELOPED AND SUCCESSFULLY DEMONSTRATED USING A 10-BAY TRUSS STRUCTURE

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RTOP 590-14-21

**Research Objective:** Successful implementation of High Authority Control (HAC) for precise performance requires an accurate system model. Analytical models are usually not sufficiently accurate for high performance design, and existing methods to obtain experimental models require extensive modal testing using random inputs or sine-sweep inputs. The objective of this research is to develop an identification algorithm for flexible structures that is fast, yet sufficiently accurate to facilitate quick model updating, hence improves turn-around time for control design and implementation.

**Approach:** A recursive identification scheme is employed. Recursive techniques, however, require a description of the system in a regressive form, such as the auto-regressive moving-average or ARMA model which usually not convenient for modern control design. Direct ARMA representation from state-space models requires identifying a large number of Markov parameters (impulse response functions), especially for lightly damped, large flexible systems. This shortcoming is circumvented by developing a technique that identifies the Markov parameters of a mathematical observer system instead. The observer is made asymptotically stable by eigenvalue assignment, hence the observer model does not require as many Markov parameters to be identified as for the actual system. Markov parameters of the actual systems can be recovered from the identified observer Markov parameters through algebraic relations, and then used to identify a discrete-time or continuous-time state-space model of the hardware by the existing Eigenvalue Realization Algorithm method.

**Accomplishments:** A new identification technique based on assigning eigenvalues to an observer has been developed. The technique allows placement of real, complex, or mixed real and complex eigenvalues. A special version of this algorithm, called the deadbeat algorithm, has also been developed that permits the most efficient use of data, and establishes a theoretical upper bound on the ability of any algorithm to extract a state-space model of the system from measurement data. Extensive investigation of the properties of the algorithm has been conducted. Using test data from a ten-bay truss structure driven by a single sinusoidal input, which generally is not sufficiently rich for complete modal identification, the algorithm was applied to identify a state-space model of the structure. The algorithm extracts a linear model of the system that best fits the limited data record (7 seconds long in this case). This is verified by a close agreement of the reconstructed vs. the actual responses within the 7 seconds of data used for identification using the same sinusoidal input, as well as the predicted vs. actual responses of the remaining available data for comparison.

**Significance:** A new recursive identification technique for flexible structures has been developed. This is a time domain technique that can make use of any general input-output data. Since it does not require specialized inputs, it is potentially useful for regular updating of the system model for High Authority Control, with on-line implementation. Preliminary test results indicate that the algorithm has the potential to identify the system with fewer data points than previously required.

**Future Work:** Research effort to extend the algorithm to the stochastic case is in progress. Practical aspects of the algorithm including its computational requirements will be studied for fast on-line implementation.

Figure 69 (a).



# A NEW RECURSIVE SYSTEM IDENTIFICATION METHOD DEVELOPED AND SUCCESSFULLY DEMONSTRATED USING A 10-BAY TRUSS STRUCTURE

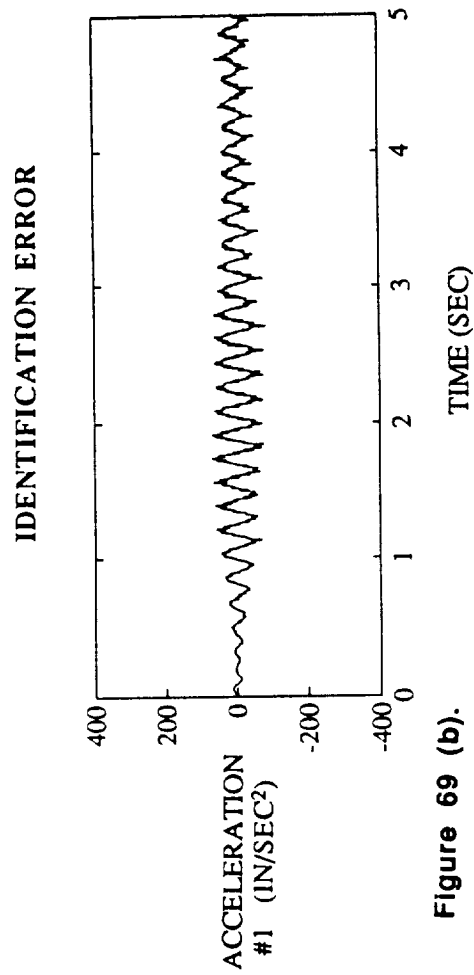
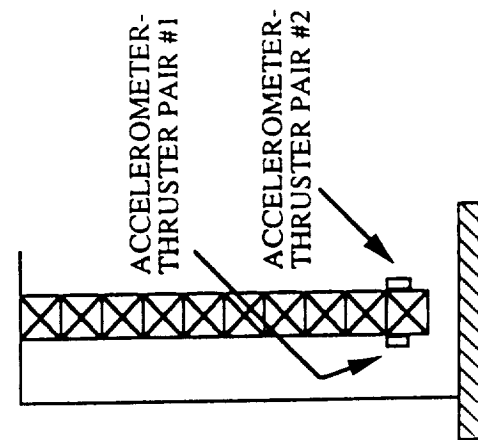
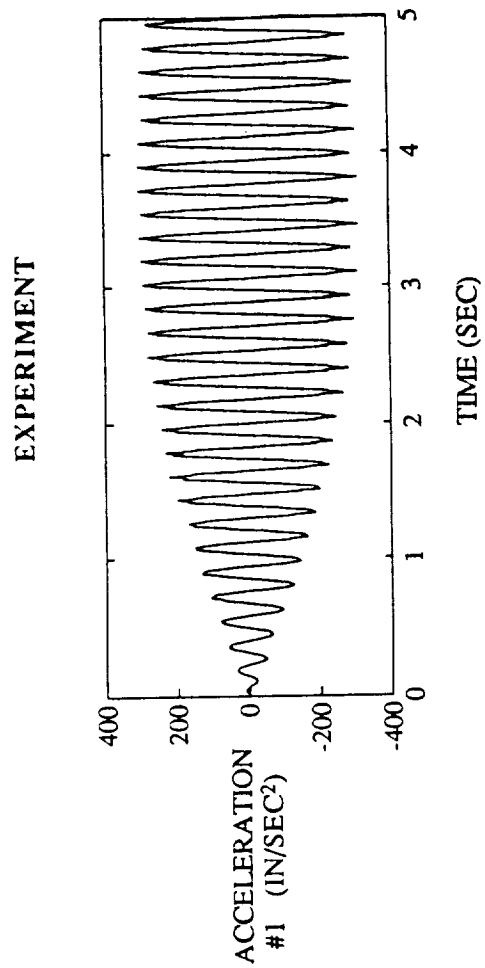
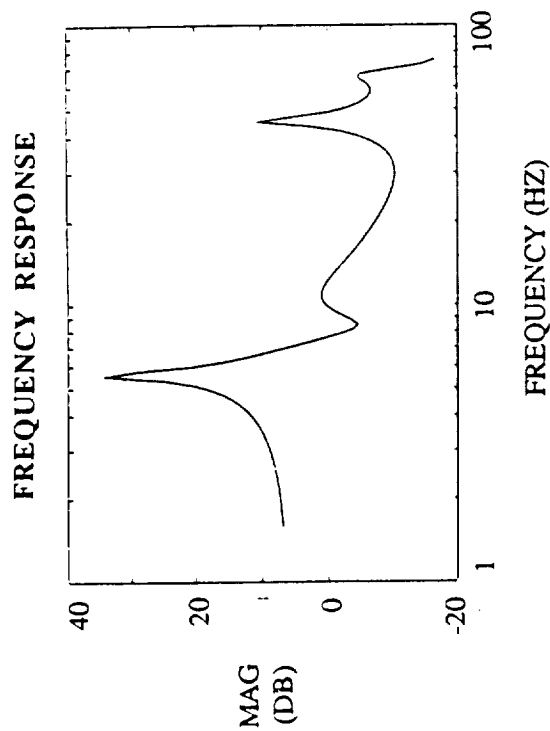


Figure 69 (b).

## METHOD DEVELOPED FOR EXPANSION OF MEASURED MODE SHAPES

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Spacecraft Dynamics Branch

RTOP 590-14-31

**Research Objective:** Estimation of unmeasured displacements in mode shapes for space truss structures based on measured dynamic response data and analytical dynamic model information.

**Approach:** Selected measured data from laboratory truss structure is used with a new expansion/orthogonalization procedure to estimate values for the remaining unmeasured displacements. A mathematical subspace defined by the measured displacements can be compared to a subspace defined by mode shapes from an analytical model of a similar structure. In computational mathematics, this problem is called the orthogonal Procrustes problem. Using the Singular Value Decomposition (SVD) of a matrix, an orthogonal rotation matrix is efficiently computed which, when applied to the analytical model modes, produces a set of mode shapes closest to those measured in the test.

**Accomplishment Description:** The approach has been used to compare the subspaces defined by the set of measured displacements and the corresponding set from the analytical model. The resulting rotation matrix is applied to the full analytical model modes to produce an estimate of the full mode shapes for the test. Since the analytical modes are orthonormal with respect to the mass matrix and since the rotation matrix is orthogonal, the expanded mode shapes are automatically orthogonal with respect to the mass matrix. No subsequent operation is necessary.

The figure depicts the test article with measured data at 8 nodes of the truss structure. The "measured" displacements that result from modal testing fill only certain values of the mode shape vector. A partial picture of the mode is seen when these values are plotted as a bar chart in the lower left figure. The orthogonal Procrustes algorithm uses measured data to produce a full column vector or a complete picture for the expanded mode. An independent correlated model produced the mode shown in the background of the lower figures. By the comparison, the expanded mode is a good approximation for the full mode shape.

**Significance:** Full mode shapes from the tests of a structure on-orbit are useful for test/analysis correlation, but are necessary for structure identification for damage location. Optimal-update identification algorithms require full mode shape vectors and assume orthogonality with respect to the mass matrix. The new expansion/orthogonalization algorithm produces mode shape vectors that satisfy both requirements. Previous expansion techniques produced vectors that required a subsequent orthogonalization process. Other studies have shown that performance of the new method is comparable or superior to that of previous expansion methods which require subsequent reorthogonalization of the estimated mode shapes.

**Future Plans:** To use the expansion/orthogonalization method in studies to locate damaged members of large space truss structures.

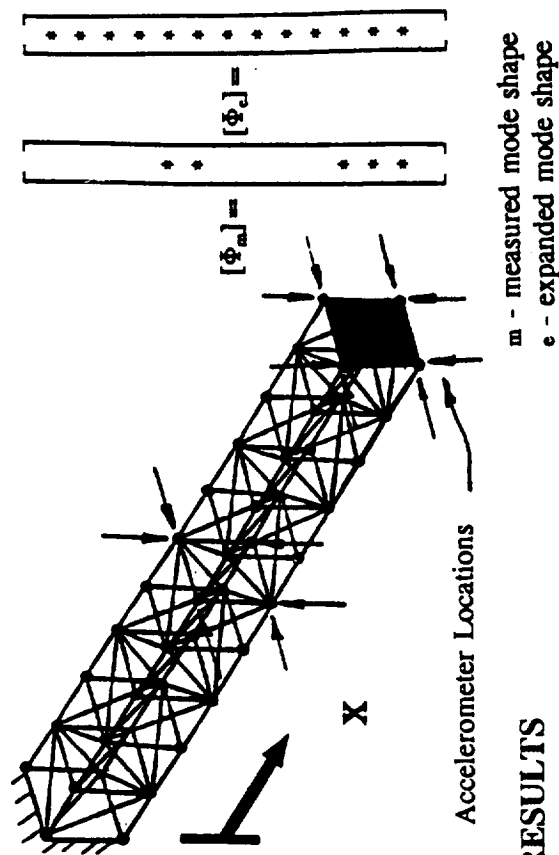
Figure 70 (a).

# METHOD DEVELOPED FOR EXPANSION OF MEASURED MODE SHAPES

## CONCEPT OF EXPANSION

- GIVEN:** A MEASURED MODE SHAPE,  $[\Phi_m]_{rx1}$  AND AN ANALYTICAL MODE SHAPE,  $[\Phi_a]_{lax1}$  ( $r \leq n$ ).
- FIND:** AN EXPANDED MODE SHAPE,  $[\Phi_e]_{lax1}$  TO MATCH THE MEASURED DATA.
- RESULT:** EXPANDED MODE IS COMPLETE AND MASS ORTHOGONAL FOR TEST/ANALYSIS CORRELATION.

## CANTILEVERED TRUSS TESTS



## EXPANSION RESULTS

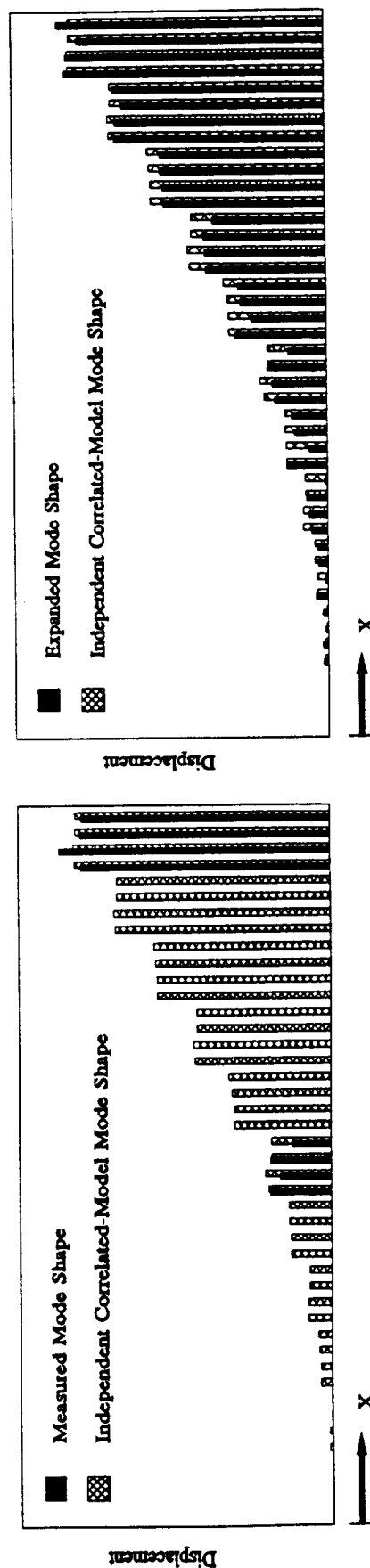


Figure 70 (b).

## NONLINEAR JOINT MODELING STUDY

Mark Webster (MIT), Wallace E. Vander Velde (MIT), and Dean W. Sparks, Jr.  
Spacecraft Controls Branch

RTOP 590-14-61

**Research Objective:** Many future space structures will consist of large, complex trusses which will inevitably include many joints. These joints will tend to have nonlinear behavior, such as jump phenomena, that may be significant to the overall dynamics of the entire structure. It is important to characterize these nonlinearities to better understand and to ultimately control the dynamics of these joint-dominated space structures. The objective of this research is to investigate ways of characterizing and modeling the dynamics of truss structures with nonlinear joints.

**Approach:** In standard practice, describing functions would be used to obtain analytical expressions to model the nonlinear joints. Typical joint-dominated trusses, however, may have hundreds of joints, making the task of modeling each individual joint impractical. Two other, more efficient methods, in terms of having fewer degrees of freedom, for handling the nonlinearities in a more global representation of trusses have been developed. The first is based on modeling the truss with an approximate continuum beam with the nonlinear joints included as beam properties which vary with the excitation amplitude. The second method models sections of the truss as single finite element beams with nonlinear spring attachments between beams. Using these methods, simple two-dimensional, single and double bay, trusses with joint nonlinearities were analytically examined. To help extend this work to more realistic trusses, experimental data was taken on the Mini-Mast Testbed using forward and backward sine sweep excitation tests, from which some nonlinear behavior was identified.

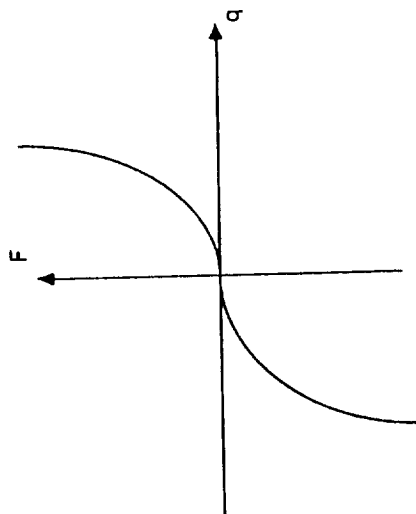
**Accomplishments Description:** Describing functions, which model such joint nonlinearity phenomena as freeplay, Coulomb friction and cubic spring, have been developed and incorporated into simple, two-dimensional truss models. The figure on the left side shows the describing function expression for a cubic spring; the  $cp1$  parameter is related to the equivalent stiffness of the cubic spring. The upper right figures show sample end displacement and end rotation responses, respectively, for a single bay, two-dimensional cantilevered truss model (with nonlinearities represented by cubic springs), due to varying end force excitation amplitudes. Initial test data taken from the Mini-Mast Testbed show some nonlinear behavior which can be attributed to the joints. The lower right figure is a sample frequency response plot of the results of two separate forward sine sweeps. Both sweeps were taken over the same frequency range, however, the excitation amplitude for one was 2.25 times that of the other. The response due to the higher forcing amplitude peaked at a lower frequency than that of the other. This phenomena was also observed in forward and backward sine sweeps at the same excitation amplitudes; the peak responses would occur at different frequencies, depending on the direction of the sweep.

**Significance:** This work is useful in practical modeling of nonlinearities of joint-dominated trusses. By better understanding the joint nonlinearities which are inevitably present in such structures, better dynamical models of the overall structures can be obtained for use in control system design.

**Future Plans:** The continuum beam describing function modeling method will be further developed. Using the test data taken from the Mini-Mast Testbed, a model (with nonlinearities represented) of the Mini-Mast will be derived using this method.

Figure 71 (a).

Describing function for cubic spring



Cubic Spring

$$c_1 = \frac{2}{\pi Q} \int_0^{\pi} \left[ \frac{AE}{L} (A_1 + B_1)^3 + K_1 \left( \frac{AE}{K_3 L} \right) (A_1 + B_1) \right] \sin \phi d\phi$$

$$A_1 = \left\{ \frac{q}{2} + \sqrt{\frac{q^2}{4} + \left( \frac{AE}{27K_3 L} \right) \left( \frac{K_1 L}{AE} + 2 \right)} \right\}^{\frac{1}{3}}$$

$$B_1 = \left\{ \frac{q}{2} - \sqrt{\frac{q^2}{4} + \left( \frac{AE}{27K_3 L} \right) \left( \frac{K_1 L}{AE} + 2 \right)} \right\}^{\frac{1}{3}}$$

$$q = Q \sin \phi$$

$$\phi = \omega t$$

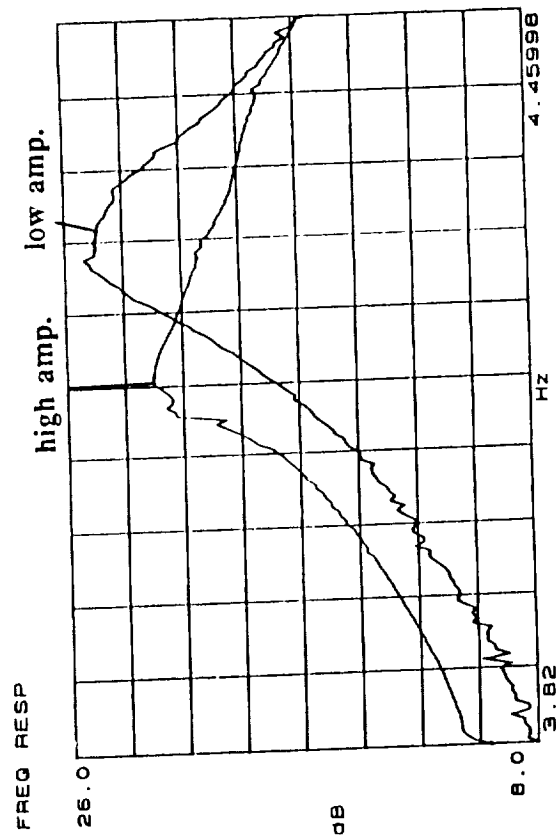
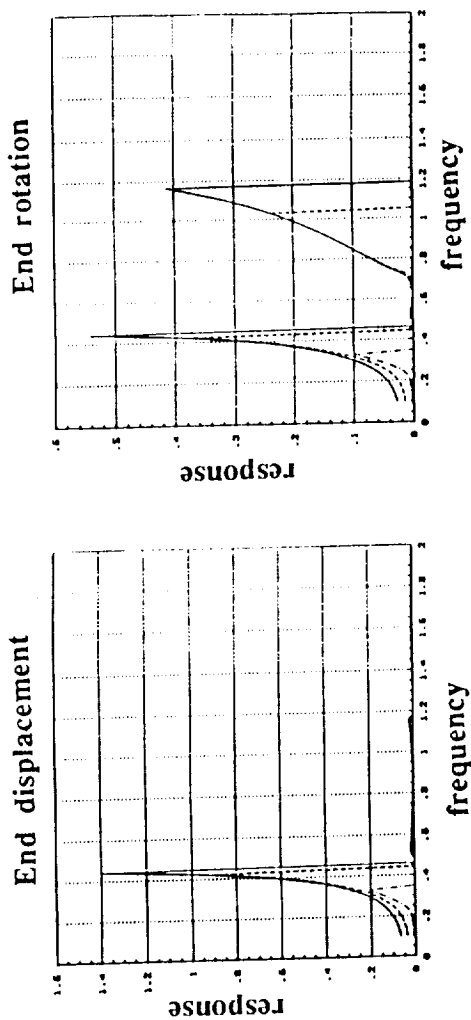
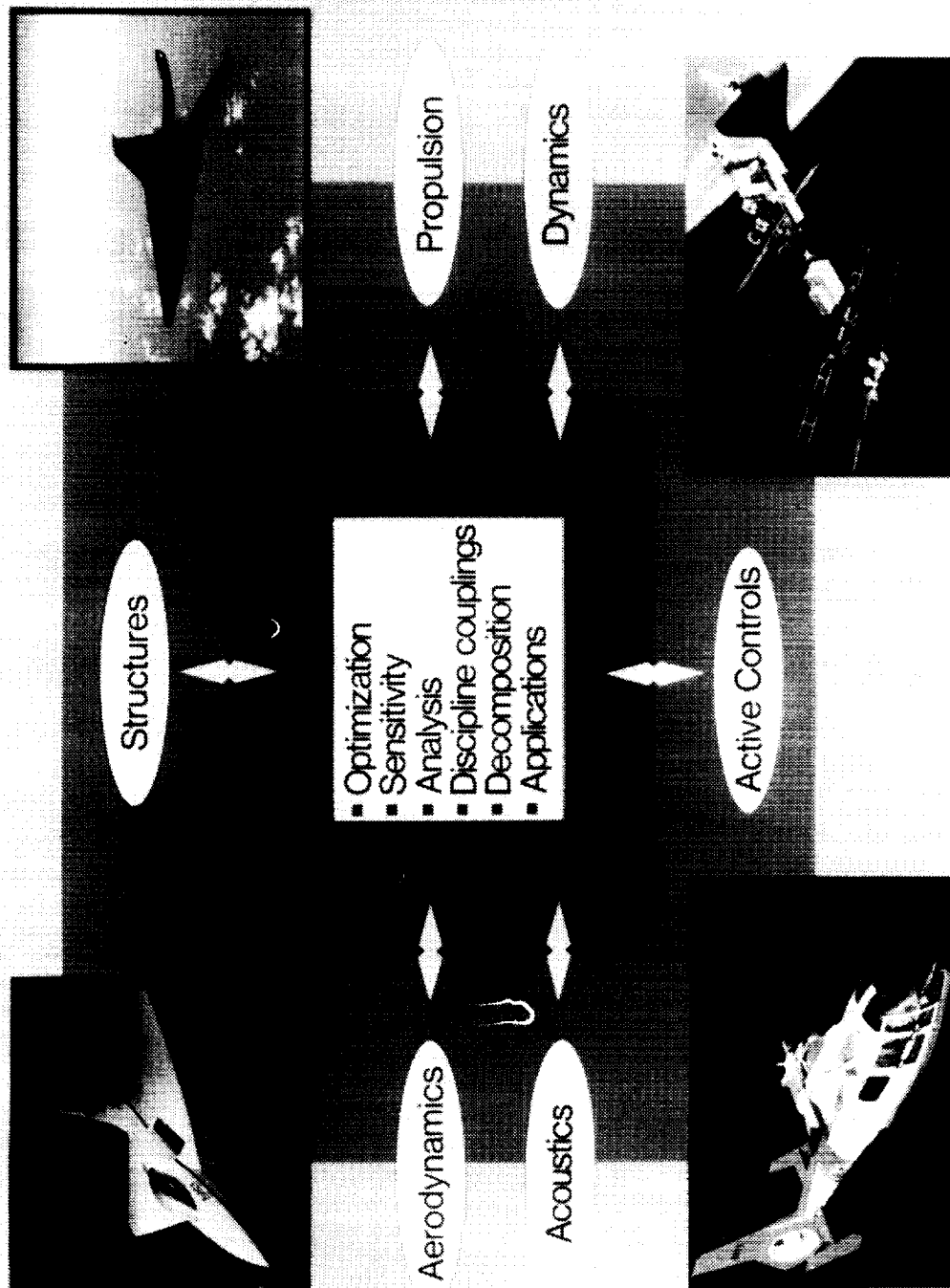


Figure 71 (b).

# INTERDISCIPLINARY RESEARCH



*'The whole is greater than the sum of the parts'*  
Aristotle

**Figure 72.**

# INTERDISCIPLINARY RESEARCH FUTURE PLANS (FY 91-95)

GOAL  
DEVELOP COMPREHENSIVE METHODOLOGY FOR OPTIMAL MULTI-DISCIPLINARY DESIGN

KEY OBJECTIVES

- METHODOLOGY

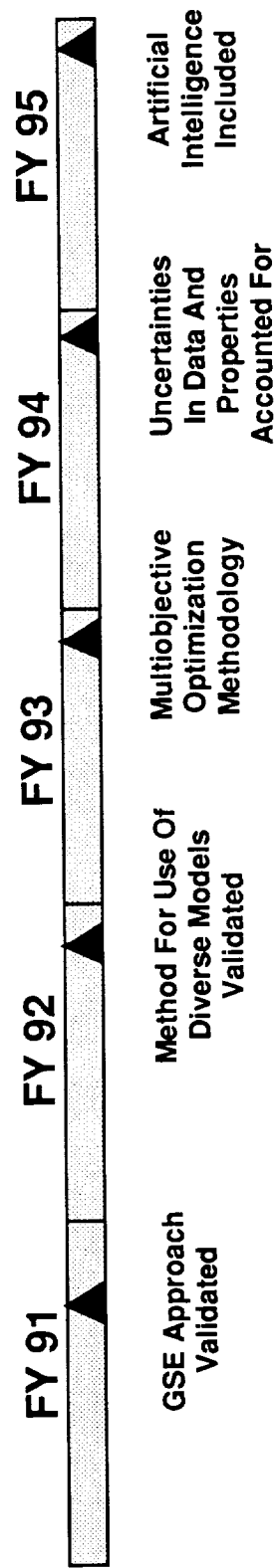


Figure 73 (a).

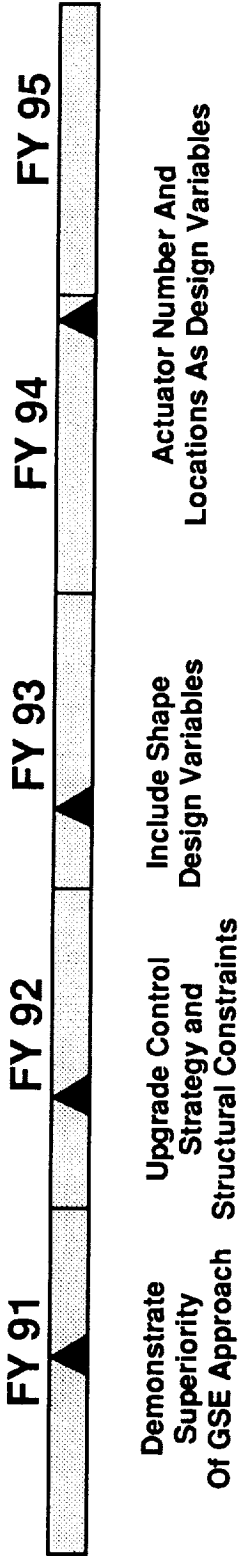
# INTERDISCIPLINARY RESEARCH FUTURE PLANS (FY 91-95)

**GOAL**

**DEMONSTRATE OPTIMAL DESIGN**

**KEY OBJECTIVES**

- ACTIVE CONTROLLED SPACE STRUCTURES



- HIGH SPEED CIVIL TRANSPORT

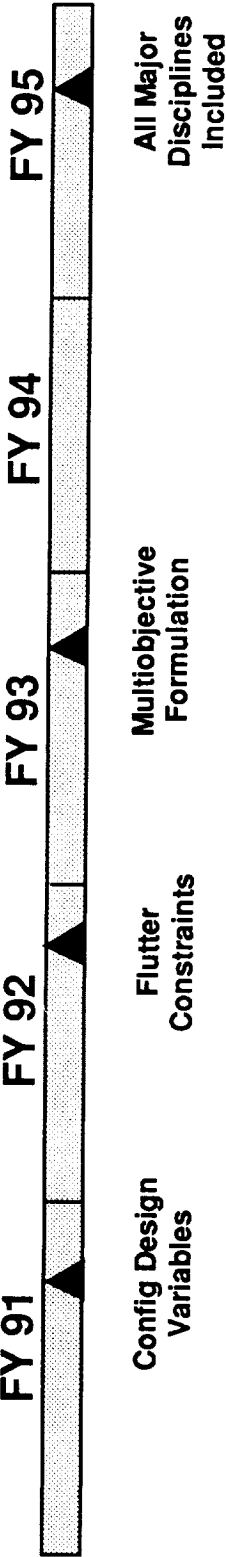


Figure 73 (b).



# INTERDISCIPLINARY RESEARCH FUTURE PLANS (FY 91-95)

GOAL

DEMONSTRATE OPTIMAL DESIGN

KEY OBJECTIVES

- ROTORCRAFT

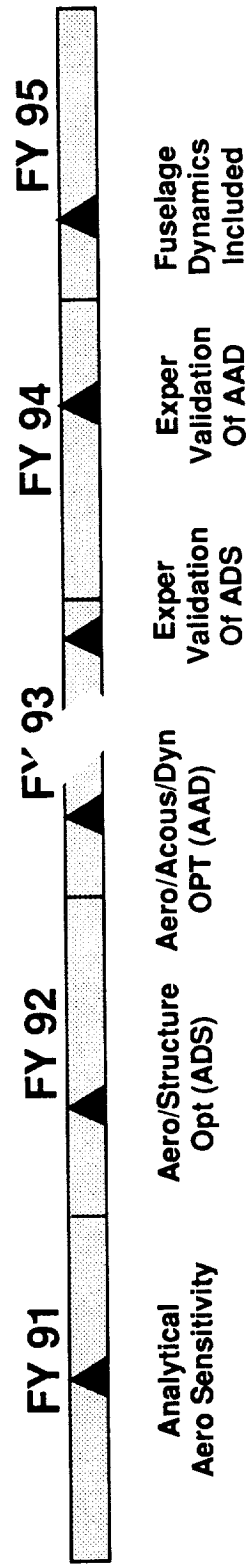


Figure 73 (c).

## INTEGRATED ROTORCRAFT OPTIMIZATION

Howard M. Adelman  
Interdisciplinary Research Office

RTOP 505-63-36

**Objective:** Integrated multidisciplinary analysis and optimization methods offer significant advantages for aircraft and spacecraft design and performance. The current work is intended to exploit this phenomenon by developing and validating a helicopter rotor design procedure wherein aerodynamics, dynamics, structures, and acoustics are fully integrated.

**Approach:** Optimization methods for the individual disciplines of aerodynamic performance, rotor dynamics, and blade structures will be developed and validated. These three optimization procedures will be systematically merged to form the integrated procedure. The influences of acoustics and airframe dynamics will be accounted for initially as effective constraints on designs based on the first three disciplines. In later work, acoustics and airframe dynamics analyses will be more fully integrated with the other disciplines.

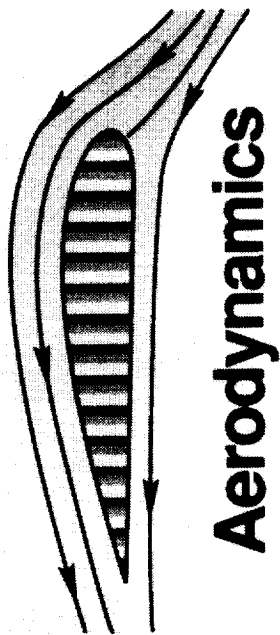
**Accomplishment Descriptions:** The joint NASA/Army activity at Langley on integrated rotorcraft optimization continues to progress well. During the past year a significant milestone was reached with the publishing of a comprehensive plan and approach with accomplishments in the document referred to as a "white paper." The paper was distributed to all of the U. S. rotorcraft companies for their critique. This was followed by a series of visits by the Langley researchers to the companies. The result of the visits was very positive. The work is viewed by industry as an appropriate role for the agency and they expressed interest in following and participating in the work.

**Significance:** The integrated rotorcraft optimization activity has received an endorsement from the helicopter industry as a potential supplier of analytical design technology. Industry input to this activity has contributed to a balancing of the program between basic research and shorter term technology transfer activities.

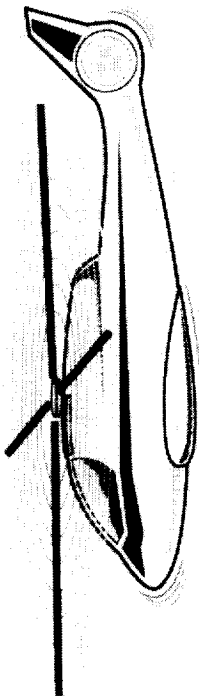
**Future Plans:** The principal emphasis during the next year will be on completing the aerodynamic/dynamic integration, structural optimization and integrating acoustics analyses with aerodynamic performance optimization. Also the first steps have been taken towards developing a series of validation experiments to confirm the optimization results obtained to date.

Figure 74 (a).

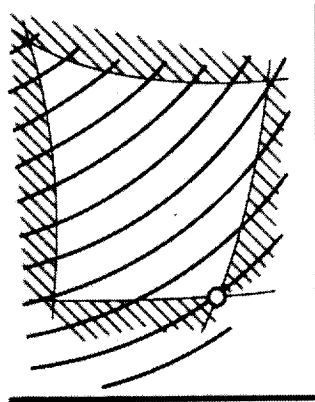
# INTEGRATED ROTORCRAFT OPTIMIZATION



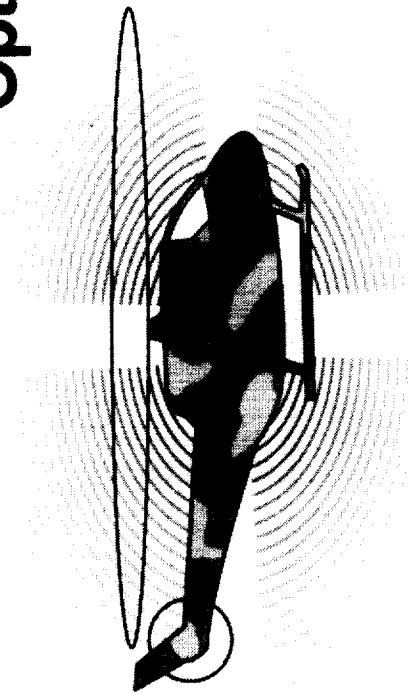
**Aerodynamics**



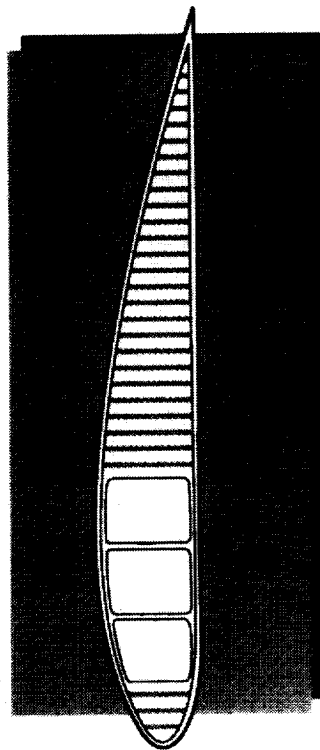
**Dynamics**



**Optimization**



**Acoustics**



**Structures**

Figure 74 (b).

# INTEGRATED CONTROLS-STRUCTURES OPTIMIZATION FOR A LARGE SPACE STRUCTURE

Sharon L. Padula  
Interdisciplinary Research Office

RTOP 506-43-41

**Research Objective:** To develop integrated optimization methods for large space structures in which controls-structures interaction (CSI) plays a dominant role.

**Approach:** Future Agency missions such as Mission to Planet Earth, envision large space structures which will require control systems to damp out vibrations due to excitations such as motion of articulated payloads and pointing maneuvers. There is strong evidence that an optimized design which considers CSI effects will have significant cost and performance benefits not possible if the control system and structure are designed separately. However, developing an optimization method which coordinates general purpose structural analysis and optimal control software and which incorporates all appropriate structural and control system constraints is a challenge.

The flowchart on the attached figure summarizes a new method for CSI optimization. The method was developed and tested by application to the COFS-1 mast flight system (MFS). The initialization step prepares the structural analysis model of the mast using initial values of design variables such as truss member cross-sectional properties and mast dimensions. Initial values of parameters characterizing weight budget and control strategy are also selected. The next step performs a structural optimization to find the best compromise between all the design requirements given the current weight budget. The optimal control step finds the best control settings given the reduced model of the optimized structures. This step also calculates the total power requirements for this design. The final step predicts whether changes in the weight budget or control strategy could reduce the total system weight (i.e. structural weight + power generating equipment weight). If improvement is possible, system parameters are reset and then the process continues.

**Accomplishment:** The method was applied to three different configurations of the COFS-1 MFS. In each case, the method successfully reduced the total weight of the system by about 20%. Results comparing the final results for the three configurations are shown on the right side of the figure. The graph shows the weight associated with the structure ( $W_s$ ), the weight associated with power generation ( $c \cdot P_{tot}$ ) and the total weight ( $W_{tot}$ ). It is interesting to note that the 42-bay configuration had the smallest structural weight but the largest total weight. This emphasizes the need for integrated Controls-Structures optimization.

**Significance:** This project is the first CSI optimization to use general purpose controls and structures software and one of the first applied to a design problem with a significant number of degrees of freedom and with realistic design constraints.

**Future Plans:** The initial application (COFS-1 MFS) is a simplified CSI design in that the number, mass and location of actuators and sensors is fixed and in that the loading conditions are idealized. The next application (already in progress) is to design a free flying Earth Observing Satellite and is considerably more challenging in these respects.

Figure 75 (a).

# INTEGRATED CONTROLS-STRUCTURES OPTIMIZATION FOR A LARGE SPACE STRUCTURE

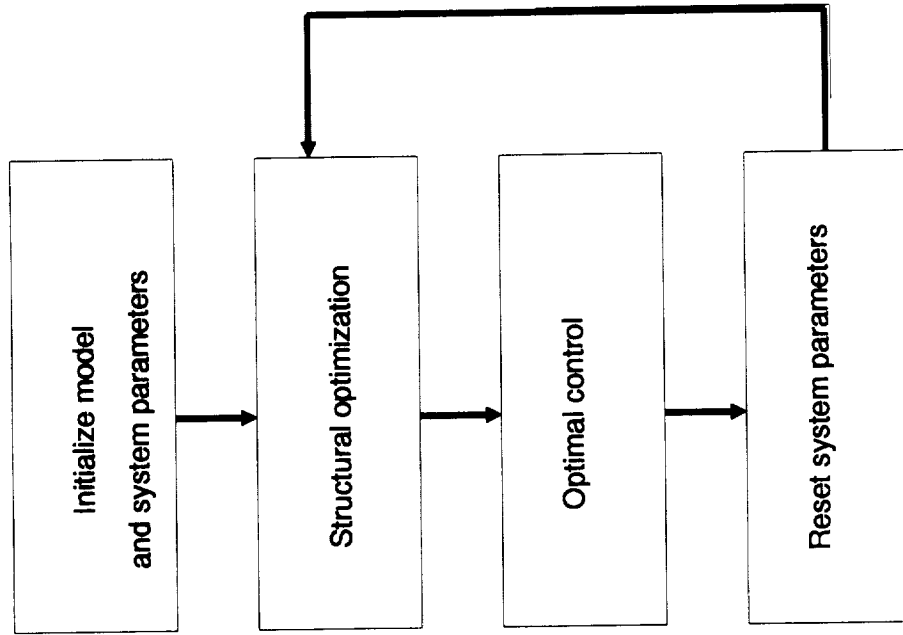
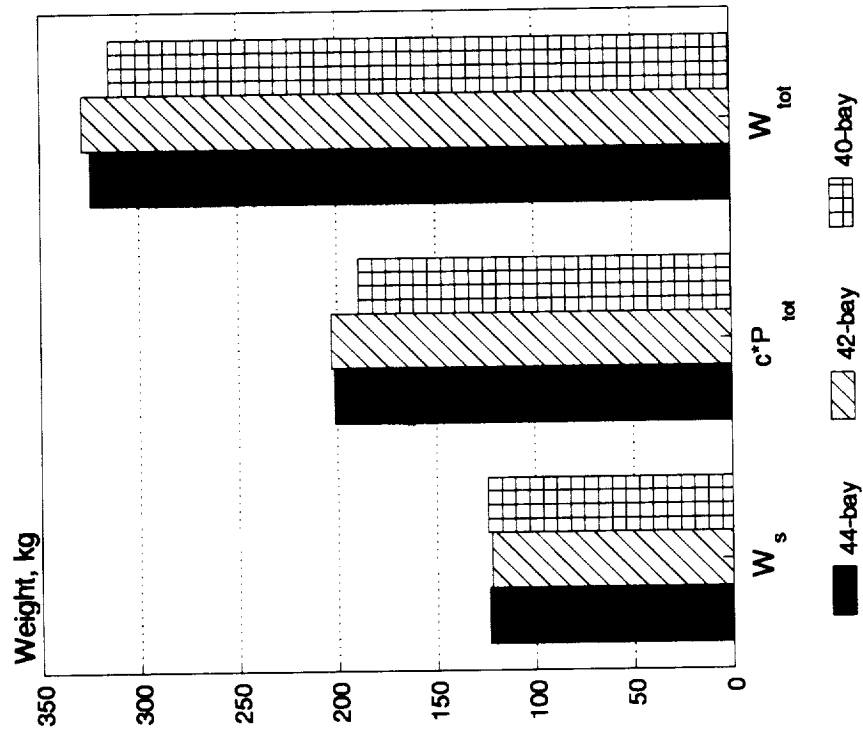


Figure 75 (b).

## MODEL ROTOR BLADE SUCCESSFULLY OPTIMIZED FOR HOVER PERFORMANCE

Joanne L. Walsh  
Interdisciplinary Research Office

RTOP 505-63-36

**Research Objective:** This work is part of a Langley Research Center effort to integrate various disciplines in rotor blade design optimization. The present work deals with hover performance optimization.

**Approach:** A procedure is developed to minimize the hover horsepower of rotor blades by selecting the point of taper initiation ( $r/R$ ), root chord ( $c_r$ ), taper ratio ( $c_r/c_t$ ), and maximum twist ( $\tau_{max}$ ) where  $R$  is the blade radius and  $c_t$  is the tip chord (see fig. 76(b)). The procedure uses HOVT (a strip theory momentum analysis) for hover and the comprehensive helicopter analysis program CAMRAD for forward flight and maneuver. The optimization algorithm consists of the general purpose optimization program CONMIN and approximate analyses. Sensitivity analyses consisting of derivatives of the objective function and constraints are carried out by finite differences. Satisfactory aerodynamic performance is defined by requirements which are enforced for three flight conditions: hover, forward flight at advance ratio  $m=0.3$  and maneuver at a load factor of 1.2 and  $m=0.3$ . The requirements are: the required horsepower must be less than the available horsepower; blade airfoil section stall on the retreating side of the rotor disc must be avoided; the drag divergence on the advancing side of the rotor disc must be avoided; and the blade must be trimmed. The blade airfoil section stall and the divergence drag avoidance are handled by limiting the largest coefficient of drag along the blade at various azimuthal locations.

**Accomplishment Description:** The coupling of HOVT, CAMRAD, and CONMIN has been accomplished. Results have been obtained for nonuniform inflow (no wake) for hover and nonuniform inflow (rigid wake) for forward flight and maneuver. As shown in figure 76(b), the optimized design has moved the point of taper initiation significantly outboard and reduced the root chord by 31%. A significant decrease in the hover horsepower (denoted by power coefficient  $C_p$  in the figures) has been obtained and the horsepower for the other flight conditions has decreased as well. Specifically, the optimized design has an improvement of six percent in hover horsepower, 11% in forward flight, and 0.5% in maneuver horsepower. As shown in figure 76(c), the optimized design also has improved performance at various forward flight speeds which is an additional benefit since the blade was designed for improved hover performance.

**Significance:** This optimization procedure uses CAMRAD for performance optimization for the first time and incorporates wake models for forward flight and maneuver flight conditions. The procedure forms the basis for the integrated rotor blade design optimization.

**Future Plans:** Include the effects of elastic stiffness of the rotor blade. Add dynamics to produce a fully-integrated aerodynamic/dynamics optimization procedure.

Figure 76 (a).

# MODEL ROTOR BLADE SUCCESSFULLY OPTIMIZED FOR HOVER PERFORMANCE

## Design requirements

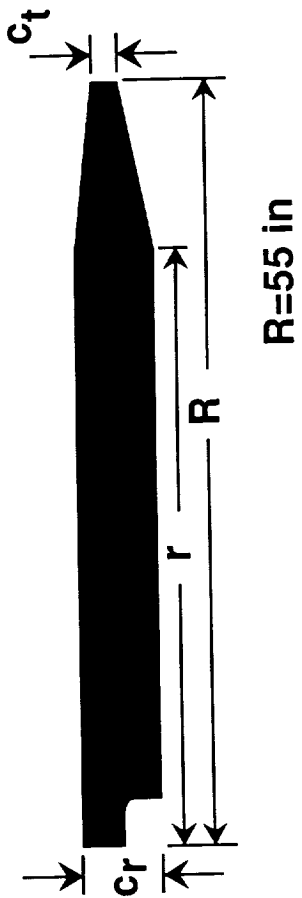
Minimum hover horsepower

hp req ≤ hp avail

No airfoil stall

Blade must be trimmed

} For 3 flight conditions



## Design variables

Taper initiation  $r/R$

Blade root chord  $c_r$

Taper ratio  $c_r/c_t$

Maximum twist  $\tau_{max}$

	Initial	Optimum
$r/R$	0.8	0.86
$c_r$ (in)	5.4	3.7
$c_r/c_t$	3.0	2.4
$\tau_{max}$ (deg)	-16.0	-15.2
Hover $C_p$	.00052	.00049
Forward flight $C_p$	.00042	.00038
Maneuver $C_p$	.00047	.00047

Figure 76 (b).

# MODEL ROTOR BLADE SUCCESSFULLY OPTIMIZED FOR HOVER PERFORMANCE

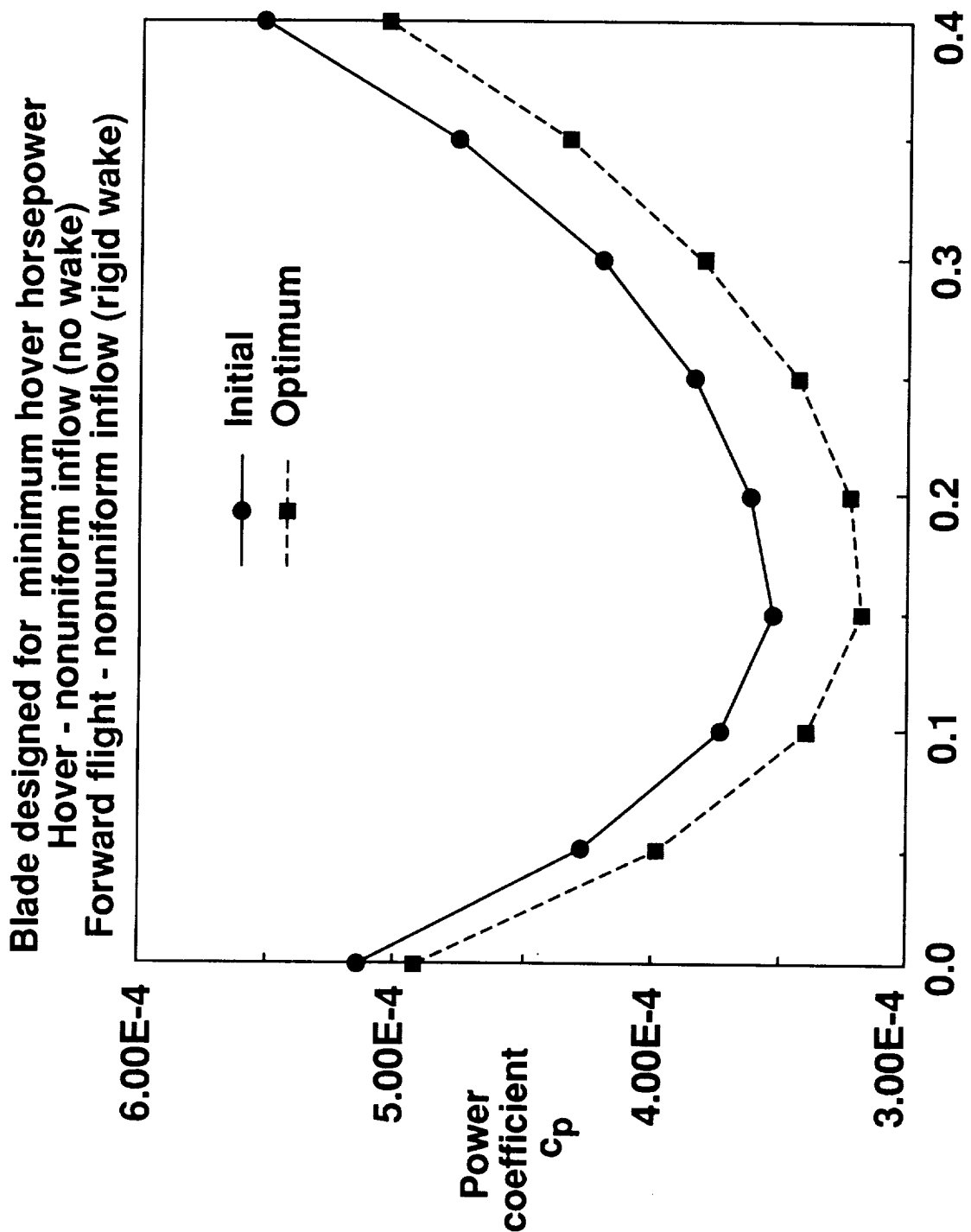


Figure 76 (c).



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# AERODYNAMIC SENSITIVITY ANALYSIS CAPABILITY DEVELOPED FOR HELICOPTER ROTORS IN AXIAL FLIGHT

Y. Danny Chiu, Lockheed Engineering and Science Company  
Interdisciplinary Research Office

RTOP 505-63-36

**Research Objective:** Develop aerodynamic sensitivity analysis procedures for helicopter rotors in axial flight to be used in aerodynamic performance optimization.

**Approach:** The method is based on 3-Dimensional Lifting-Line theory with an undistorted wake model. Analytical expressions for aerodynamic sensitivity derivatives for rotary wings in axial flight have been formulated as an integro differential equation in terms of derivatives of circulation with respect to shape design variables. The shape design variables are taper ratio, tip shape, solidity, inplane curvature rate, out-of-plane curvature rate, dihedral rate, twist ratio, and twist shape. The governing equations for the aerodynamic functions and derivatives have been solved by using two discretization methods: the Multhopp Interpolation Technique and the Vortex Lattice Method.

**Accomplishment Description:** Results have indicated that the aerodynamic functions and derivatives are equally accurate from both discretization methods but are sensitive to the number of discretization panels and terms. For a reasonable number of terms of panels (M-20), the methods provide 4 digits of accuracy for aerodynamic functions and 2 digits of accuracy for aerodynamic derivatives. Results also provide the effect of each design variable in rotor design. For example, the lift-drag ratio ( $C_L/CD_i$ ) is inversely proportional to the taper ratio ( $\lambda$ ) as shown in the left part of the figure. Therefore, the triangular blade ( $\lambda=0$ ) is more efficient than the rectangular blade ( $\lambda=1$ ). In the right side of the figure ( $\partial(C_L/CD_i)/\partial\lambda$ ) represents the derivative which can be applied to rotor performance optimization. Also, results from analytical methods agree well with finite difference derivatives as shown in the right side of the figure.

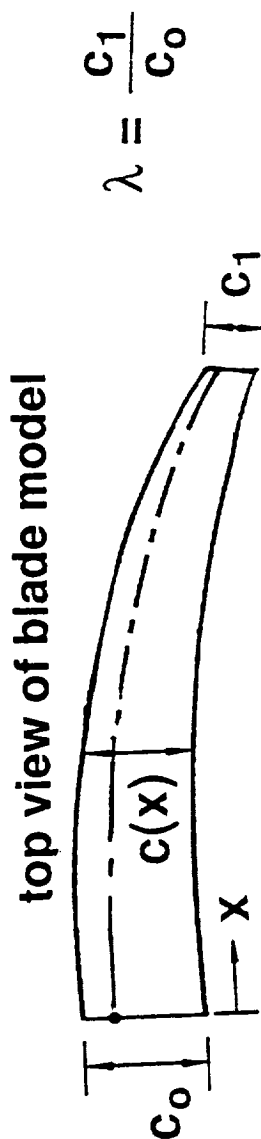
**Significance:** Aerodynamic sensitivity analysis is critical in aerodynamic shape optimization as well as for optimization which involves integrating aerodynamics with other disciplines. The present method provides exact solutions for aerodynamic derivatives which avoid numerical errors associated with finite difference derivatives.

**Future Plan:** The influence of different wake modes will be investigated. The method will then be extended for aerodynamic sensitivity for rotary wings in forward flight.

Figure 77 (a).

# AERODYNAMIC SENSITIVITY ANALYSIS CAPABILITY DEVELOPED FOR HELICOPTER ROTORS IN AXIAL FLIGHT

Objective: Develop aerodynamic sensitivity analysis procedures for helicopter rotors in axial flight using undistorted wake model of steady lifting-line theory for optimization applications.



Example: Derivative of lift-drag ratio with respect to taper ratio

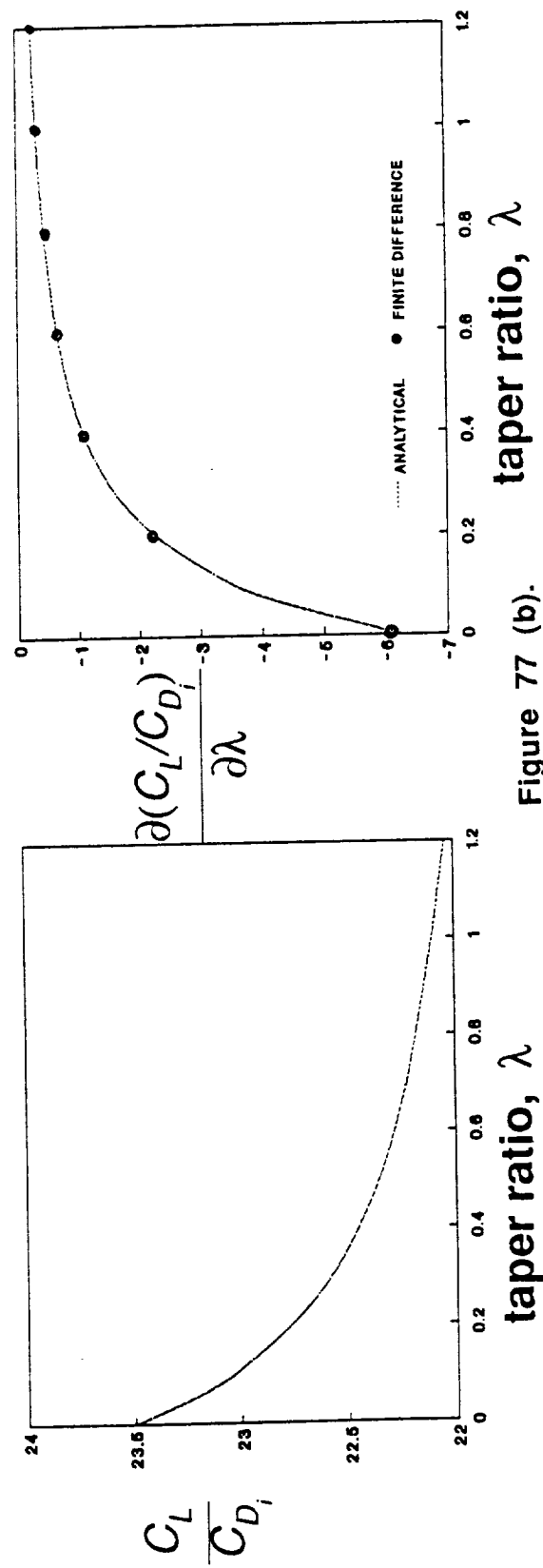


Figure 77 (b).

# SHAPE SENSITIVITY ANALYSIS OF STATIC AND DYNAMIC AEROELASTIC RESPONSES

Rakesh K. Kapania and Lloyd B. Eldred, Virginia Polytechnic Institute and State University

Jean-Francois M. Barthelemy  
Interdisciplinary Research Office

RTOP 505-63-01

**Research Objective:** Develop and implement methodology for shape sensitivity analysis of static and dynamic aeroelastic responses.

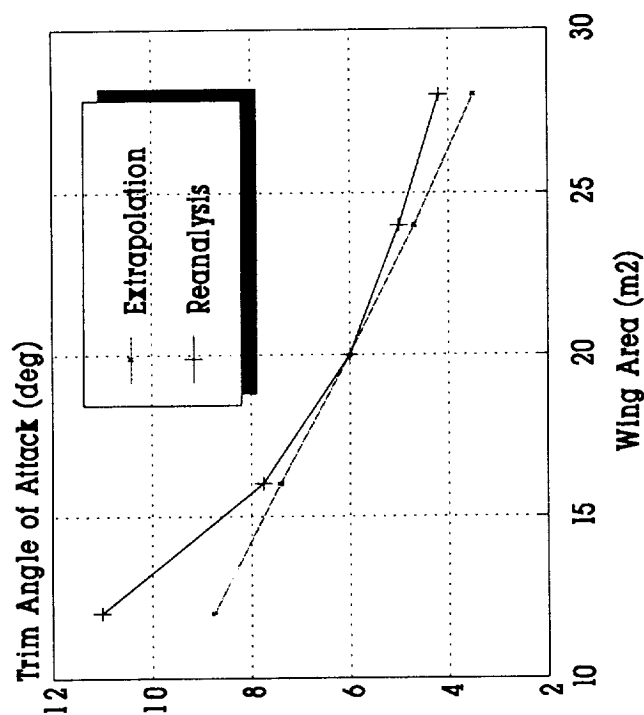
**Approach:** A variation of Sobieski's Global Sensitivity Equations (GSE) approach is implemented to obtain the sensitivity of the static aeroelastic response of a three dimensional wing model. The formulation is quite general and accepts any aerodynamic and structural analysis capability. It assumes that for a given shape and elastic deformation, the aerodynamic analysis will provide the pressure distribution on the wing. Similarly, the structural analysis needs to provide only the elastic deformation of the wing, given its shape and pressure distribution. An interface code is written to convert one analysis' output to the other's input, and visa versa. Local sensitivity derivatives are calculated by either analytic methods or finite difference techniques. A program to combine the local sensitivity, such as the sensitivity of the stiffness matrix of the aerodynamic kernel matrix, into global sensitivity derivatives is developed.

**Accomplishment Description:** The aerodynamic package FAST, using a lifting surface theory, and a structural package, ELAPS, implementing Giles' equivalent plate model are used. A Chebyshev polynomial series is used to represent the pressure output of the aerodynamic analysis. An iterative scheme is used to determine a converged state for the wing model. Local sensitivity derivatives are calculated for the converged wing. A global sensitivity code has been developed to combine the local sensitivities and the converged wing data into global sensitivity derivatives of the static aeroelastic responses. Excellent results have been obtained for sensitivity of the required wing angle of attack and of the converged wing deflected shape to changes in wing area (see figure). Sensitivity results with respect to sweep, aspect ratio and taper ratio are being obtained. Anticipating the future need for obtaining the sensitivity of the flutter characteristics and the stability margins for the aeroservoelastic design, it was decided to use an aerodynamic model that is described in the first-order state space form (as opposed to the frequency domain representation). For a two degree-of-freedom airfoil section model, the sensitivity derivatives of the flutter speed are obtained for a number of pertinent variables. Two approaches, namely (i) analytic and (ii) finite difference were used. Excellent agreement was observed between the two sets of results (see table).

**Significance of Accomplishments:** The present scheme is independent of the analysis codes used. The static aeroelastic responses, in general, are obtained only after performing an expensive iterative analysis. It is very expensive to obtain these responses for every design modification. For small changes, the present approach can avoid performing these expensive iterative analyses and can thus be used for optimization purposes.

**Future Plans:** The experience gained in using the state space form aerodynamic model for determining the sensitivity of the flutter characteristics for a two degree-of-freedom airfoil section model can easily be extended to obtaining the sensitivity derivatives of a three dimensional wing. The key problem is to represent the unsteady aerodynamics of three dimensional wing in a finite state form.

Figure 78 (a).



Variation of Trim Angle of attack with Wing Area (Base Configuration Wing Area=20 m<sup>2</sup>, Aspect Ratio = 7.5, Taper Ratio = 0.5, Sweep Angle = -15°)

Parameter	Analytic Sensitivity	Finite Difference .01%
Static Unbalance	162.56	162.56
Radius of Gyration	-0.0546	-0.0514
Mass Ratio	0.519	0.519
Distance between elastic axis and a.c.	6.24	6.24
Bending Frequency	1.61	1.61

Sensitivity of Flutter Speed with respect to various variables for a 2 degree-of-freedom airfoil section using a state space aerodynamic model

Figure 78 (b).

# DIFFERENTIAL-EQUATION-BASED METHOD PROVIDES ACCURATE APPROXIMATIONS FOR VIBRATION FREQUENCIES AND MODE SHAPES

Jocelyn I. Pritchard and Howard M. Adelman  
Interdisciplinary Research Office

RTOP 505-63-36

**Research Objective:** Develop and validate a method to efficiently and accurately approximate the effect of design changes on structural vibration frequencies and mode shapes.

**Approach:** The classical formulas for the sensitivity of frequencies and mode shapes are interpreted as differential equations which may be solved for closed form exponential approximations. This approach results in highly accurate approximations to changes in frequencies and mode shapes due to design perturbations in the neighborhood of nominal designs.

**Accomplishment Description:** The approximations were derived, implemented, and tested. The test cases involved a cantilever beam with perturbations of the height, width, cross-sectional area, bending stiffness, and tip mass. Results were compared with exact solutions and the commonly used Taylor Series approximation. In all cases the new approximation proved to be more accurate than the Taylor Series. For example, the figure shows a graph of the eigenvalue (the square of the first bending frequency) versus the height of the beam,  $H$  for values perturbed from the nominal value of 5.0 inches. The Taylor Series linear approximation curve deviates significantly from the exact curve at values of  $H$  away from the nominal whereas the exponential approximation result follows the exact curve. For as much as a 50% increase in  $H$ , the new approximation is within 2% of the exact solution. For sufficiently large decreases from the nominal value of  $H$  the Taylor Series approximation predicts a negative eigenvalue whereas even for a 50 % decrease in  $H$ , the new approximation is still within 17% of the exact solution.

**Significance:** It is highly desirable in optimization for structural dynamics to calculate the effect of design changes on the frequencies and mode shapes without having to perform a full eigenvalue analysis each time the design is modified. The present method provides an efficient and accurate approximation for this purpose.

**Future Plans:** The exponential approximation method will next be applied to a helicopter rotor blade model and in addition to frequencies and mode shapes, the modal shear will be approximated using this technique. The method will then be incorporated into an optimization procedure to assess its performance in an optimization environment.

Figure 79 (a).

# DIFFERENTIAL-EQUATION-BASED METHOD PROVIDES ACCURATE APPROXIMATIONS FOR VIBRATION FREQUENCIES AND MODE SHAPES

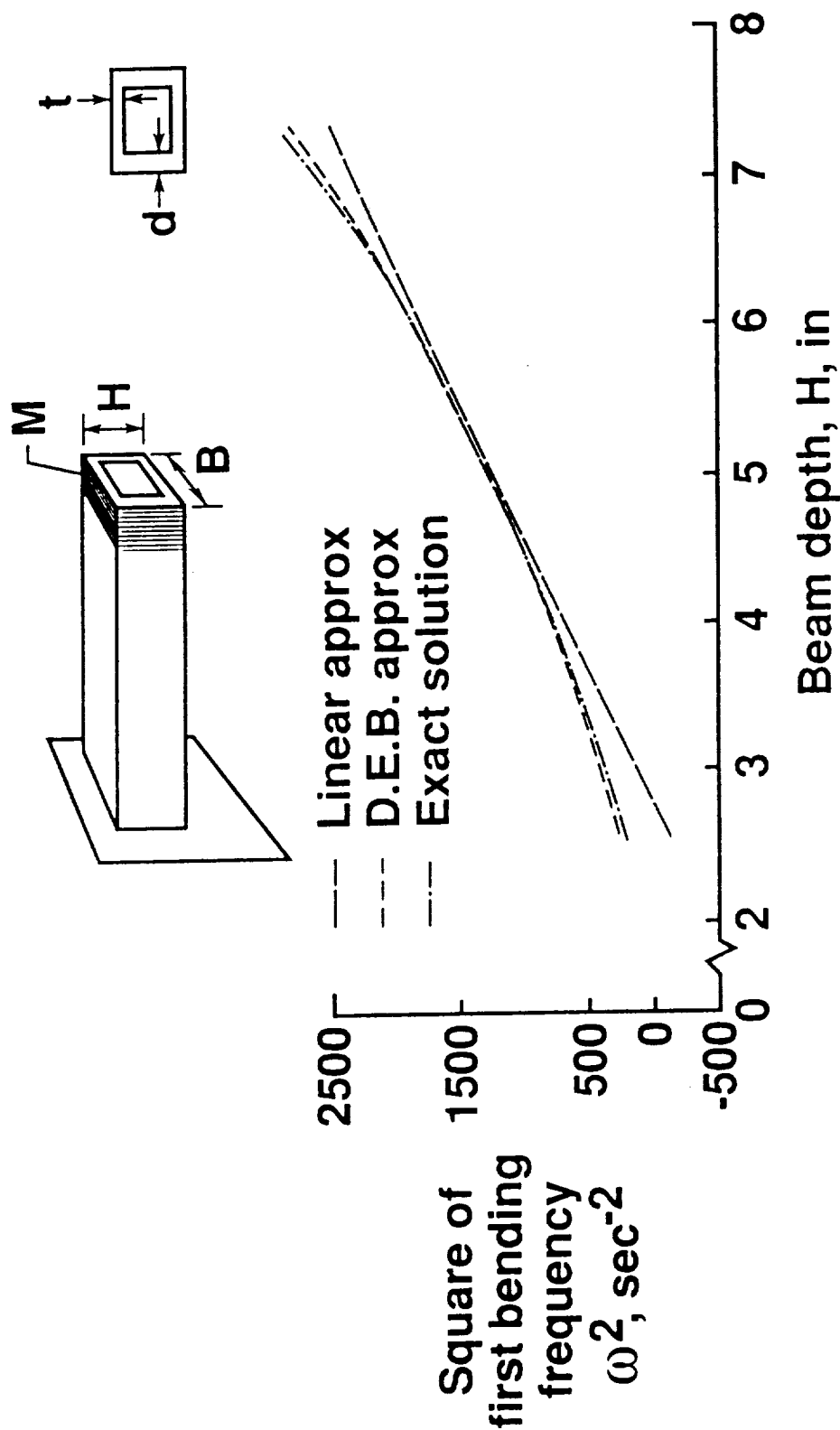


Figure 79 (b).

## COUPLED MULTIPLE-METHOD STRUCTURAL ANALYSIS DEMONSTRATED

Gary L. Giles  
Interdisciplinary Research Office

RTOP 505-63-50

**Research Objective:** To develop analytical techniques which couple different structural analysis methods in a single formulation in order to exploit the particular strengths of each method. In the present work, a beam finite element analysis is coupled with an equivalent plate analysis.

**Approach:** A recently developed analysis program, ELAPS (Equivalent Laminated Plate Solution) has been demonstrated to be effective for the preliminary design of aircraft wing structures. In the present work beam, finite elements are added to the equivalent plate modeling capability. These beam members can be used to model structural details such as store/pylon structure, landing gear, or, provide a "stick" representation of a fuselage. A schematic of the model used to demonstrate the multiple method analysis approach is shown in the left hand portion of the figure. Two plate segments are used to model the wing. The joints at the ends of the beam elements used to model the store/pylon and fuselage are indicated by circular symbols. The integrated multiple-method approach is formulated as a partitioned analysis problem shown in the upper right of the figure. The unknown quantities for the equivalent plate method are coefficients of polynomials describing the plate deformation over the wing planform. The displacements and rotations of the beam joints are the unknowns for the finite element method. Two different approaches are used to couple the methods. The first approach uses hybrid beam elements in which the displacements of the beam joints that are attached to the wing are expressed in terms of the unknown plate coefficients. The second approach uses Lagrange multipliers to express constraint equations at the interface between substructures associated with the equivalent plate and finite element models. The second approach is more general since the finite element analysis is performed in a separate program allowing a general model containing additional types of elements (e.g., membrane and bending plates, shear panels, and brick elements) to be used instead of being limited to the beam finite element model.

**Accomplishment Description:** The coupled multiple-method formulation was implemented and used to perform both a static analysis and vibration analysis of the model shown in the figure. Results were compared with results from a model composed entirely of finite elements. A typical comparison of results, deflections for the twelfth vibration mode shape, is illustrated in the lower right of the figure. The modal deflections normal to the wing planform are shown at selected semispan locations. This mode exhibits bending of the fuselage and torsion of the wing structure. Good agreement between the multiple-method and finite element results is shown. Similar results for static deflections and stresses were also found to be in good agreement.

**Significance:** The coupled formulation provides an effective structural analysis tool for use in optimization procedures, during early preliminary design. This formulation allows the analyst to take advantage of the computational efficiency and reduced model preparation time of the equivalent plate method and the general modeling capability of the finite element method. This coupled multiple-method approach can also be applied in other situations such as coupling conventional finite elements with p-method finite elements or boundary elements to perform an accurate stress analysis of a local structural detail.

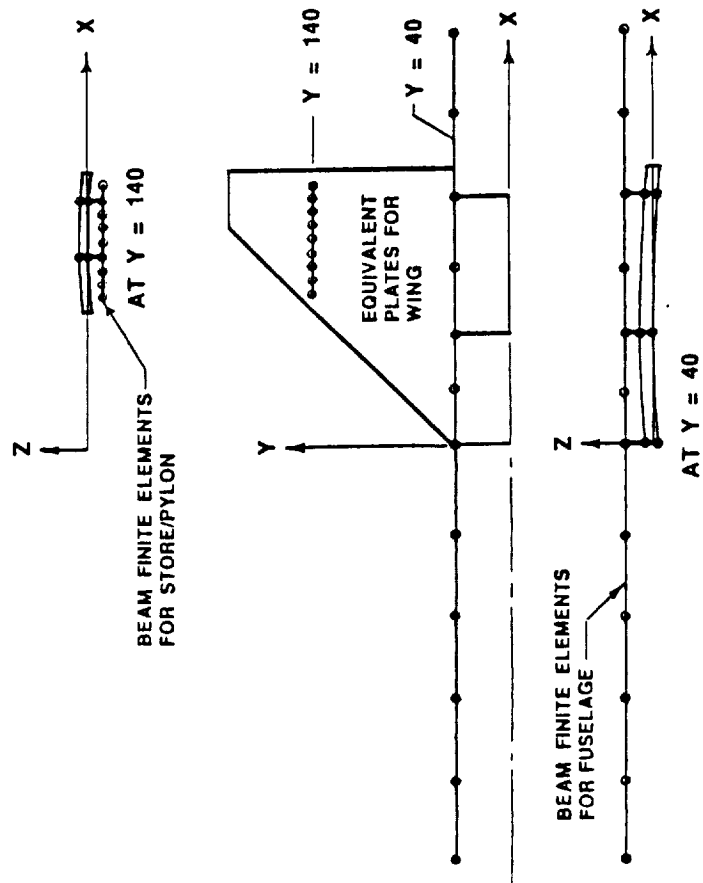
**Future Plans:** Establish cooperative agreements with industry to further demonstrate coupled multiple-method procedures.

Figure 80 (a).



# COUPLED MULTIPLE-METHOD STRUCTURAL ANALYSIS

## STRUCTURAL MODEL FOR COUPLED MULTIPLE-METHOD ANALYSIS



## COUPLED MULTIPLE-METHOD FORMULATION

Present formulation (using hybrid elements)

$$\begin{bmatrix} K_{eq. plate} + K_{hybrid} \\ K_{interface} \end{bmatrix} \begin{bmatrix} T \\ T \end{bmatrix} = \begin{bmatrix} K_{interface} \\ K_{beams} + K_{hybrid} \end{bmatrix} \begin{bmatrix} Poly. coeff. \\ Joint displ. \end{bmatrix} = \begin{bmatrix} Gen. forces \\ Joint forces \end{bmatrix}$$

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## TWELFTH VIBRATION MODE SHAPE

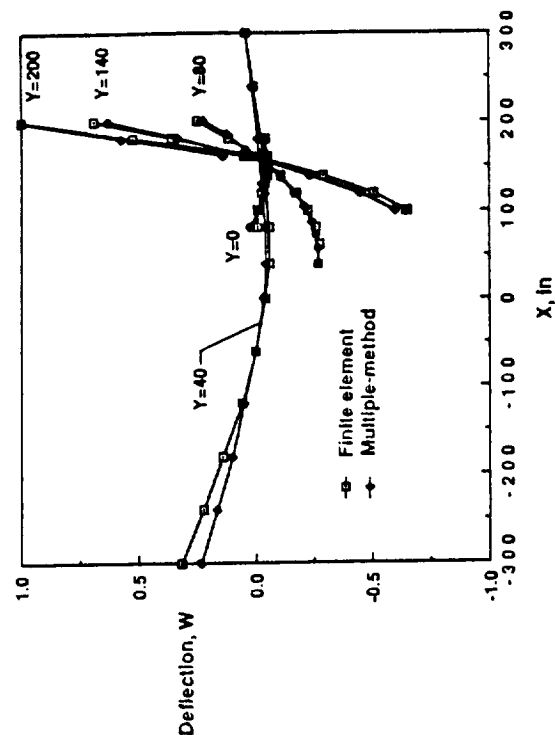


Figure 80 (b).

## APPLICATION OF A KNOWLEDGE-BASED TOOL TO UNDERSTAND HISAIR DATA FLOW

James L. Rogers  
Interdisciplinary Research Office

RTOP 505-63-01

**Research Objective:** To apply a knowledge-based tool as an aide in determining the data flow among the disciplines in the HiSAIR design project.

**Approach:** The HiSAIR design project requires data from numerous disciplines with each discipline applying one or more computer programs to generate design data. The responsible engineer for each discipline knows what data is used within that discipline and what data is generated by that discipline, but does not necessarily know what other disciplines supply or use this data. DeMAID (Design Manager's Aide for Intelligent Decomposition) is a knowledge-based tool which was recently developed to aid a design manager in the design of a new concept such as the HiSAIR aircraft. DeMAID requires as input a list of modules, the output they generate, and their input requirements. This type of data can be obtained from the discipline engineers. With this data, DeMAID orders the modules to minimize feedback. In addition, iterative processes are grouped together. The result is an informative display of the modules in an NxN matrix format indicating the order in which the modules should be processed and the major interfaces among the modules.

**Accomplishment Description:** The first step was to gather the module information from the discipline engineers. This resulted in figure 1. In this figure the arrows indicated data flow from one discipline program to another. However, there is no order to the data flow, nor is there any indication as to which modules, if any, combine into an iterative process. DeMAID input data was then created from this figure. The planning function of DeMAID indicated that the output from modules PATRAN and Structural Dynamics were not being used by any other modules. The scheduling function ordered the modules and found two iterative groups of modules as shown in figure 2. The design manager interprets the NxN matrix display to understand the data flow of this design project. The boxes on the diagonal of the NxN matrix represent a design process shown in the boxes of figure 1. A vertical line entering a box indicates an input to the process. A horizontal line exiting from a box indicates an output from that process. A circle connecting a horizontal and vertical line indicates an interface between two processes. A large box around a group of smaller boxes indicates an iterative process. The design manager can now use this data to organize and optimize the design process for the HiSAIR aircraft.

**Significance:** The HiSAIR design project was in need of a tool that would aid the design team in understanding all of the processes required to complete the design and the flow among the processes. DeMAID had not yet been applied to a real design project. Thus the application resulted in improvements to the DeMAID program, which then provided the HiSAIR design team a better understanding of the data flow for the design project.

**Future Plans:** Using DeMAID is an iterative process. As the design team analyzes the current data flow, changes are made to the overall design process. New input is created for DeMAID, DeMAID is executed resulting in a new data flow. This will continue until the design manager and the design team are satisfied with the data flow of the design project.

Figure 81 (a).

# HiSAIR Phase 1

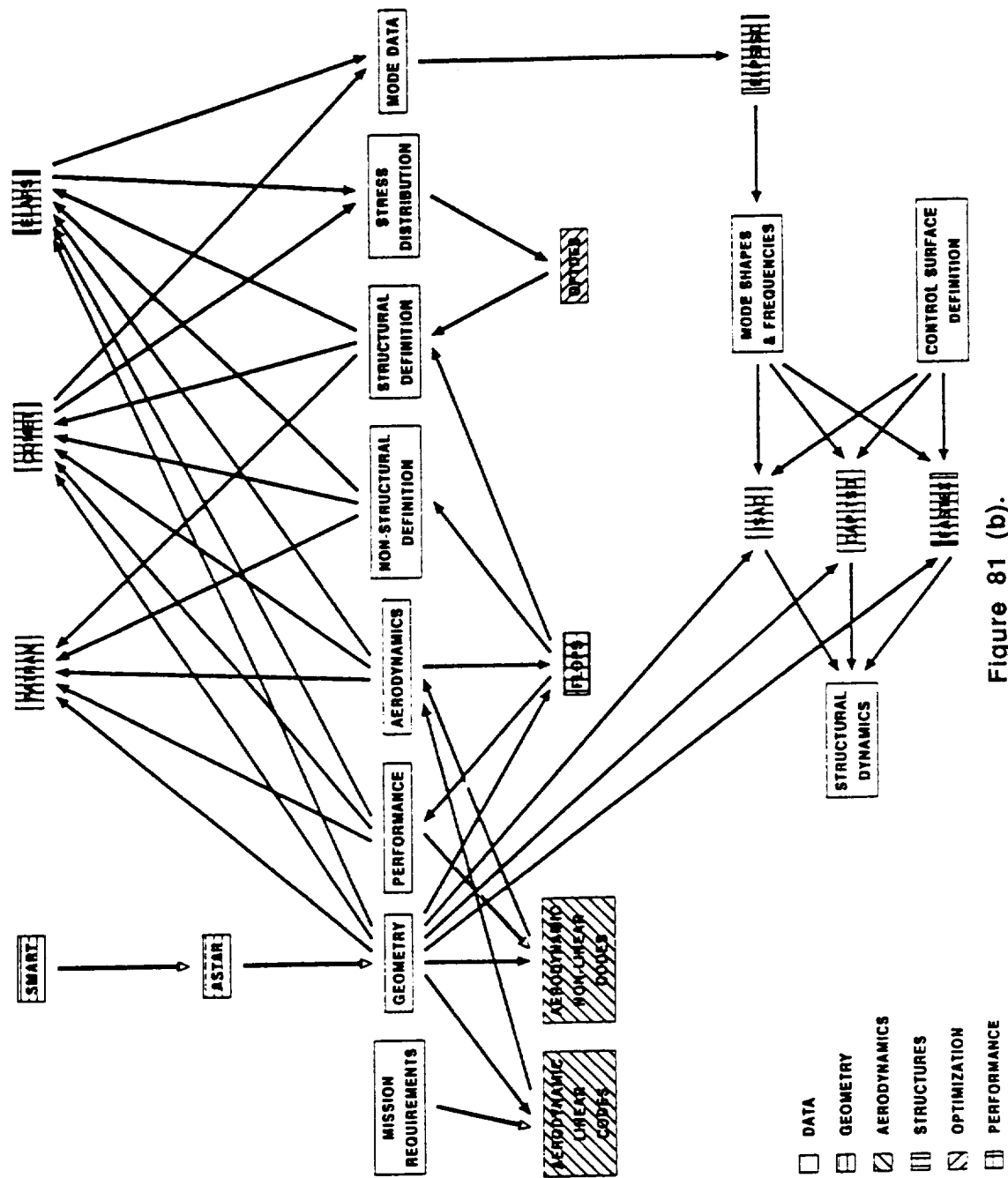


Figure 81 (b).

# NxN Matrix of HiSAIR Data

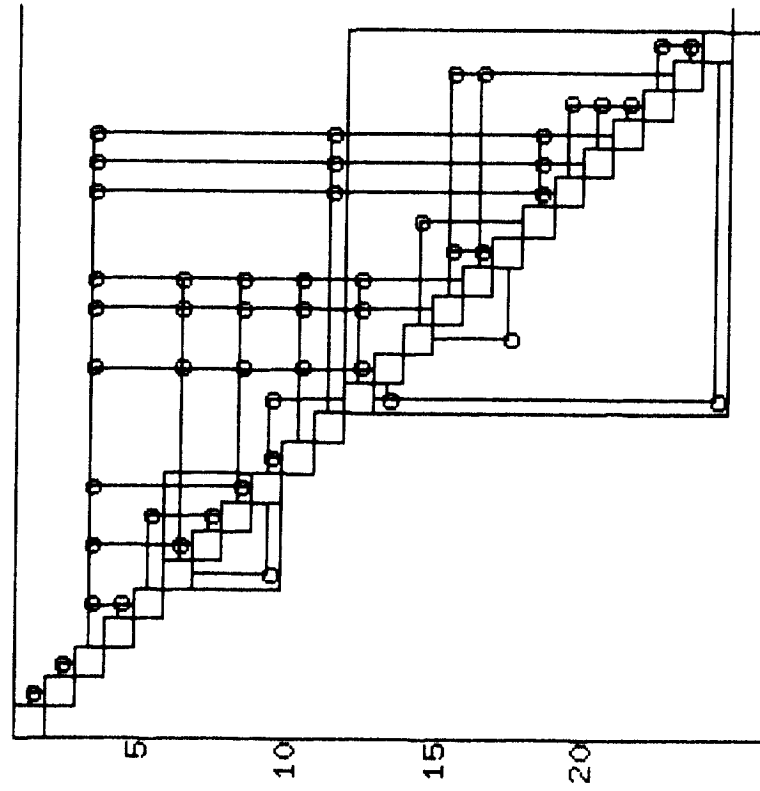


Figure 81 (c).

# CONFIGURATION AEROELASTICITY

## F.Y. 1991 PLANS

- SUPPORT CofF WORK FOR MODIFICATION OF TDT HEAVY GAS RECLAMATION SYSTEM
- COMPLETE SECOND TEST OF NACA 0012 PAPA MODEL TO ACQUIRE ADDITIONAL UNSTEADY PRESSURE DATA IN TDT
- COMPLETE TEST OF ACTIVE FLEXIBLE WING (AFW) MODEL IN TDT INCLUDING ROLL CONTROL AND ACTIVE FLUTTER SUPPRESSION
- COMPLETE INITIAL TEST OF ARES 1.5 IN TDT
- COMPLETE DESIGN AND FABRICATION OF ACTIVE CONTROLS BENCHMARK MODEL FOR VALIDATING METHODS FOR SUPPRESSION OF FLUTTER
- COMPLETE DEMONSTRATION TEST OF ARES 2.0 IN HOVER FACILITY
- COMPLETE DESIGN, FABRICATION, AND INSTRUMENTATION OF PAPA MOUNT SUPERCRITICAL WING IN PREPARATION FOR TEST IN TDT
- COMPLETE FABRICATION AHRO HUB WITH PITCH/FLAP/LAG SEQUENCE
- INITIATE ACTIVITIES IN SUPPORT OF NASP GOVERNMENT WORK PACKAGE OBJECTIVES

## AIRCRAFT AEROELASTICITY

Maynard C. Sandford  
Configuration Aeroelasticity Branch

RTOP 505-63-50

**Research Objective:** The objectives in the aircraft aeroelasticity technical area are (1) to determine and solve the aeroelastic problems of current designs, and (2) to develop the aeroelastic understanding and prediction capabilities needed to apply new aerodynamic and structural concepts to future flight vehicles.

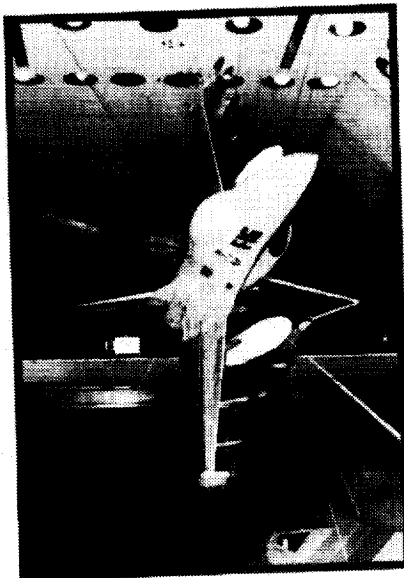
**Approach:** The types of research included in the aeroelasticity area are illustrated in CAB figure 14(b). This research is a combination of experimental and complementary analytical studies. The experimental work focuses on the use of the Langley Transonic Dynamics Tunnel (TDT) which is specifically designed to meet the unique needs of aeroelastic testing. On occasion flight research programs are undertaken when it is necessary to simulate important parameters that cannot be accurately accounted for in ground-based facilities. Often research is a cooperative effort with other government agencies and/or industry.

**Status/Plans:** Work for the coming year includes several activities, some of which are described as follows. Analytical and experimental investigations will continue to provide flutter data in support of the High-Speed Civil Transport (HSCT). A second test will be conducted on the Active Flexible Wing (AFW) model for simultaneous roll control and active flutter suppression. Joint study efforts will continue with National Aero-Space Plane (NASP) contractors, primarily McDonnell Douglas and Rockwell International. The NASP related work load will escalate significantly if three Government Work Packages on vehicle flutter evaluation, engine inlet flutter evaluation, and panel/shell flutter submitted recently are approved as expected.

Figure 83 (a).

# AIRCRAFT AEROELASTICITY

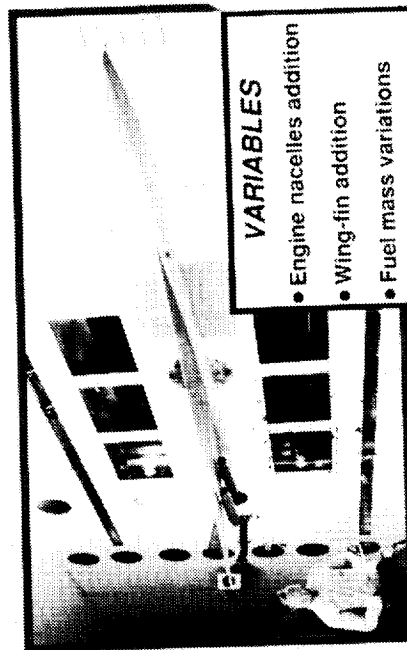
## CLEARANCE STUDIES



## RESEARCH AREAS

- Flutter
- Divergence
- Active/passive controls
- Aeroelastic tailoring
- Test techniques
- Buzz
- Buffet

## CONFIGURATION STUDIES



## VARIABLES

- Engine nacelles addition
- Wing-fin addition
- Fuel mass variations
- Angle of attack changes

## BASIC STUDIES



## FLUTTER RESULTS

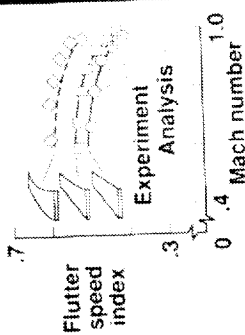


Figure 83 (b).

## ROTORCRAFT AEROELASTICITY

William T. Yeager, Jr. (ASTD)  
Configuration Aeroelasticity Branch

RTOP 505-63-36

**Research Objective:** The objectives in this technical area are to (1) conduct research in the aeroelastic, aerodynamic, and dynamic characteristics of rotors; (2) support design of advanced performance rotorcraft in the areas of loads, vibration, aeroelastic stability, and rotor performance; and (3) develop the experimental and analytical techniques necessary to extend wind tunnel and laboratory capabilities to future research requirements and opportunities.

**Approach:** This research area is a joint effort of SDyD and the U.S. Army Aerostructures Directorate which is collocated at Langley. The in-house civil research is supplemented by industry contracts and university grants. As indicated in figure 84(b), experimental studies are conducted in the TDT and the General Rotor Aeroelasticity Laboratory (GRAL). Analytical studies include the use of existing methods and the development of new and improved methods. The Aeroelastic Rotor Experimental System (ARES) testbed is key to the conduct of experimental studies. This testbed, which has drive mechanisms, a strain-gage force and moment balance, and other equipment housed in a generic fuselage shape, provides a means for studying a variety of rotor systems in simulated forward flight in the TDT and in hover in the GRAL. Two advanced versions of the ARES are being developed which make it possible to better model the coupling of the rotor and the body. The ARES 1.5 design mounts the metric section of the existing ARES testbed on a static gimbal or "soft mount" to allow adjustment of the model fixed-system stiffness and damping characteristics in both pitch and roll. The ARES II design mounts the metric section of the ARES testbed on a platform supported by six computer controlled hydraulic actuators which are used to obtain the desired body roll, pitch, yaw, side, normal and axial motion.

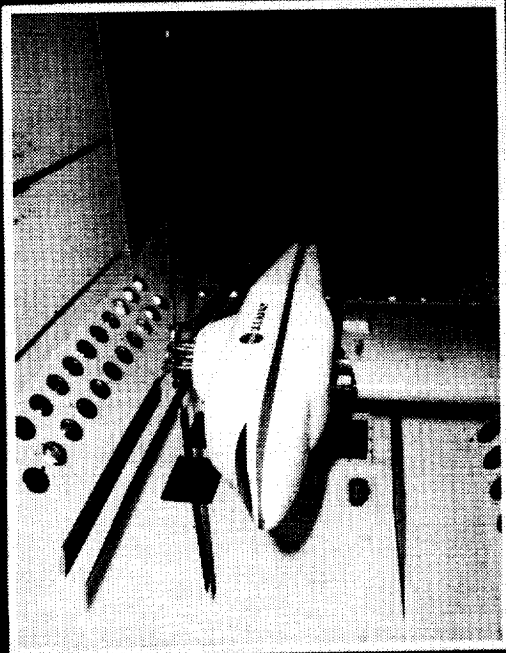
**Status/Plans:** All parts of the ARES 1.5 testbed have been fabricated and assembled. System frequency and damping characteristics have been determined, and hover tests and wind tunnel tests have been conducted in the GRAL and the TDT. Fabrication has also been completed on parts for the ARES II testbed and assembly and initial checkout in the GRAL should take place in C.Y.1991. Additionally, a closed-loop analog controller for ARES II has been developed in-house. A test in the TDT of a second-generation ARES hingeless rotor (AHRO II) was conducted to provide data for expansion of the aeromechanical stability data base. In C.Y.1991, a design for another parametric hingeless hub with a pitch-flap-lag hinge sequence will be developed. The design of a Parametric Bearingless Hub (PBH) has been completed and fabrication of hardware has begun. A Syracuse University grant to modify the CAMRAD code to provide the capability of analyzing multiple-load-path rotors is continuing.

Figure 84 (a).



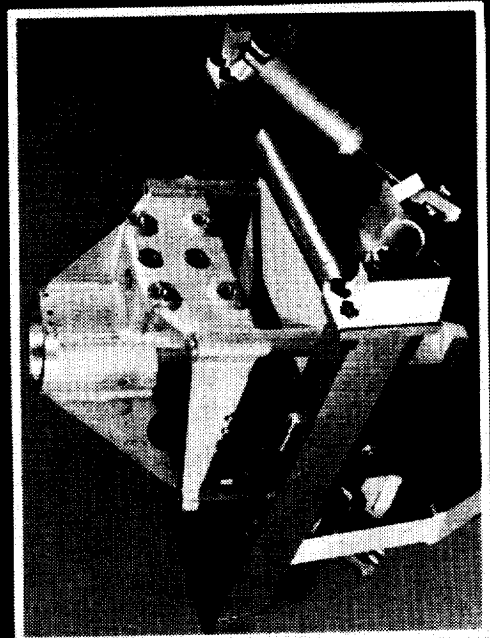
# ROTORCRAFT AEROELASTICITY

## ARES TESTBED



- RESEARCH AREAS
- Aeromechanical stability
  - Rotor performance
  - Vibration reduction
  - Rotor acoustics

## ARES II ACTIVE CONTROL SUPPORT



## ADVANCED HINGELESS ROTOR

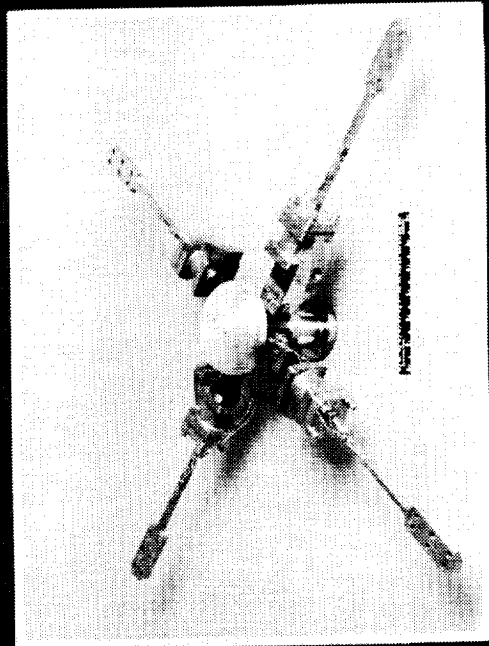


Figure 84 (b).

## BENCHMARK MODELS

Michael H. Durham  
Configuration Aeroelasticity Branch

RTOP 505-63-50

**Research Objective:** The objectives of the Benchmark Models technical area are to: (1) provide test data for evaluating new computational aeroelasticity codes, (2) increase physical understanding of unsteady flow phenomena, and (3) provide test data for developing empirical design methods where computational methods need further development.

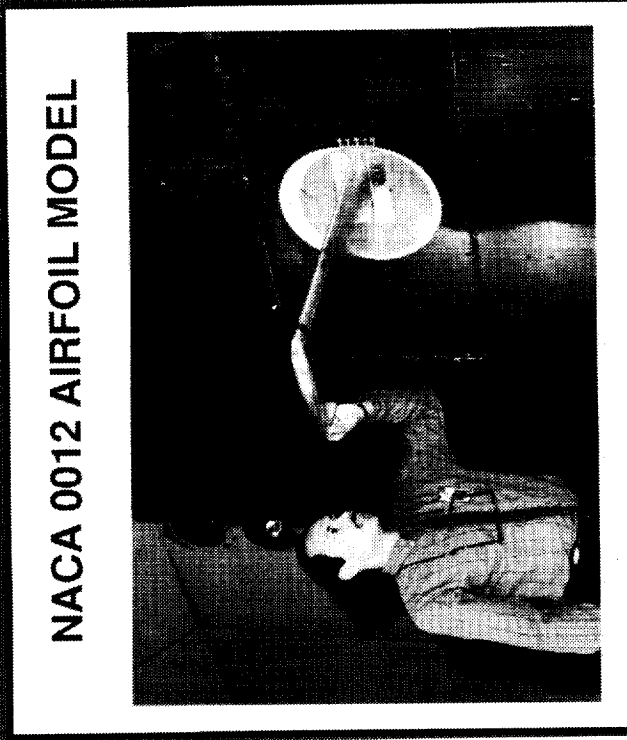
**Approach:** The Benchmark Models Program is a Structural Dynamics Division research effort involving the Configuration Aeroelasticity Branch, the Unsteady Aerodynamics Branch, and the Aeroservoelasticity Branch. The primary approach is to test instrumented well-defined dynamic models as shown in figure 83(b) up to unstable flight conditions while recording unsteady pressures, dynamic loads, and quantitative flow visualizations. Planned areas of testing for this multi-year program include measurements of conventional transonic flutter, limit-cycle oscillation flutter, non-classical flutter, the effects of vortex flows on flutter, and burst-vortex induced buffeting.

**Status/Plans:** The design and fabrication of a series of instrumented rigid rectangular wing models has been initiated. These rigid models are to be tested on a flexible mount system with pitch and plunge degrees of freedom providing a well-defined dynamic system. The first model, with a NACA 0012 airfoil, successfully completed its first tunnel test in July 1990. A second test of this model is scheduled for January 1991 with additional instrumentation to provide unsteady pressure data along two chordlines. The second rigid model, which has a SC(2)-0414 supercritical airfoil, will also measure unsteady pressures along two chordlines using 80 transducers. The third rigid model similar to the NACA 0012 model but with the addition of an active trailing edge control surface plus upper and lower surface spoilers. The purpose of this active controls model is to quantitatively measure overall unsteady pressures effects and control surface effectiveness during flutter suppression. This model will also provide a simple well-defined controls testbed to explore new methods of flutter suppression such as actively controlled spoilers. Another area of research has been in shock boundary layer oscillations. Tests of an exploratory flexible rectangular circular arc airfoil model have successfully obtained limit cycle oscillations over a narrow Mach range at a reduced frequency of approximately 0.5. Future tests are planned for a model with additional instrumentation to study the high frequency content of the unsteady pressure distributions during these limit cycle oscillations.

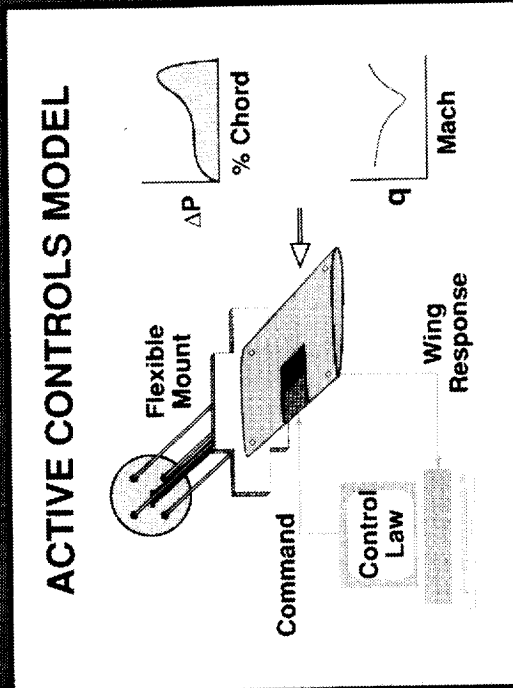
Figure 85 (a).

# BENCHMARK MODELS

**NACA 0012 AIRFOIL MODEL**



**FLEXIBLE CIRCULAR ARC  
AIRFOIL MODEL**

A black and white photograph showing a man in a white shirt and tie holding a long, thin, curved airfoil model. He is standing in front of a large, dark, curved structure, possibly a wind tunnel or aircraft fuselage. The airfoil model is held vertically, and the man is looking at it. The background is dark and industrial.

**Figure 85 (b).**

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# UNSTEADY AERODYNAMICS

## F.Y. 1991 PLANS

- O CAP-TSD CODE APPLICATION AND SUPPORT
  - CONTINUE IN-HOUSE AND INDUSTRY COOPERATIVE APPLICATIONS TO VERIFY CODE'S RANGE OF ACCURACY
  - CONTINUE TO PROVIDE PROGRAMMING SUPPORT
- O DEVELOP EULER AND NAVIER-STOKES CAPABILITIES FOR STEADY/UNSTEADY AERODYNAMIC ANALYSIS
  - GRID GENERATION METHODOLOGY
  - STRUCTURED GRID FLOW SOLVERS
  - UNSTRUCTURED GRID FLOW SOLVERS
  - TURBULENCE MODELING
- O DEVELOPMENT OF AEROELASTIC ANALYSIS METHODS FOR VORTEX DOMINATED AND BUFFETING FLOWS
  - COUPLED NAVIER-STOKES/ STRUCTURAL DYNAMICS PROCEDURE
  - INITIAL CODE VALIDATION STUDIES

Figure 86.

# DEMONSTRATE IMPLICIT FLUX-SPLIT EULER ALGORITHM BASED ON UNSTRUCTURED DYNAMIC MESHES THROUGH APPLICATION TO COMPLEX AIRCRAFT CONFIGURATION

John T. Batina  
Unsteady Aerodynamics Branch

RTOP 505-63-50

**Research Objective:** The objective of this research is to demonstrate an implicit flux-split algorithm for the numerical solution of the time-dependent Euler equations through application to a complex aircraft configuration. The algorithm has been applied previously to the M6 wing to predict steady flow at transonic conditions. These results compared well with experimental data and, therefore, the next step in the validation of the algorithm is performing applications for more complicated configurations.

**Approach:** The algorithm, which was developed within the Unsteady Aerodynamics Branch, involves accurate and efficient spatial and temporal discretizations of the Euler equations, based on unstructured meshes of tetrahedral grid cells. The spatial discretization involves a flux-split (upwind) approach which accounts for the local wave-propagation characteristics of the flow and captures shock waves sharply with at most one grid point within the shock structure. The flux-split discretization is naturally dissipative and consequently does not require additional artificial dissipation terms or the adjustment of free parameters to control the dissipation. Furthermore, the temporal discretization is an implicit time-integration scheme involving a Gauss-Seidel relaxation procedure. The scheme allows the selection of the step size based on the temporal accuracy dictated by the physical problem being considered, rather than on the numerical stability of the algorithm. Consequently, very large time steps may be used for rapid convergence to steady state, and an appropriate step size may be selected for unsteady cases, independent of numerical stability issues. The implicit flux-split algorithm will be demonstrated through application to the F/A-18 fighter configuration (see fig. 87(b)). The surface grid which models the fighter is shown in the figure. The modeling includes all of the major components of the vehicle, and further includes inlets beneath the aircraft and nozzles to simulate engine power effects. The unstructured tetrahedral mesh (obtained from K. Morgan and J. Peraire of the Imperial College of Science, Technology, and Medicine, London, England) that will be used in the calculations has 84,819 nodes and 451,668 tetrahedra.

**Status/Plans:** Calculations will be performed in F.Y. 1991 for this demonstration for a variety of flow conditions (freestream Mach numbers, angle of attack, reduced frequency) to determine the steady and unsteady aerodynamic characteristics of the F/A-18 fighter.

Figure 87 (a).

DEMONSTRATE IMPLICIT FLUX-SPLIT EULER ALGORITHM BASED  
ON UNSTRUCTURED DYNAMIC MESHES THROUGH APPLICATION  
TO COMPLEX AIRCRAFT CONFIGURATION

- Unstructured surface grid for F/A-18 fighter

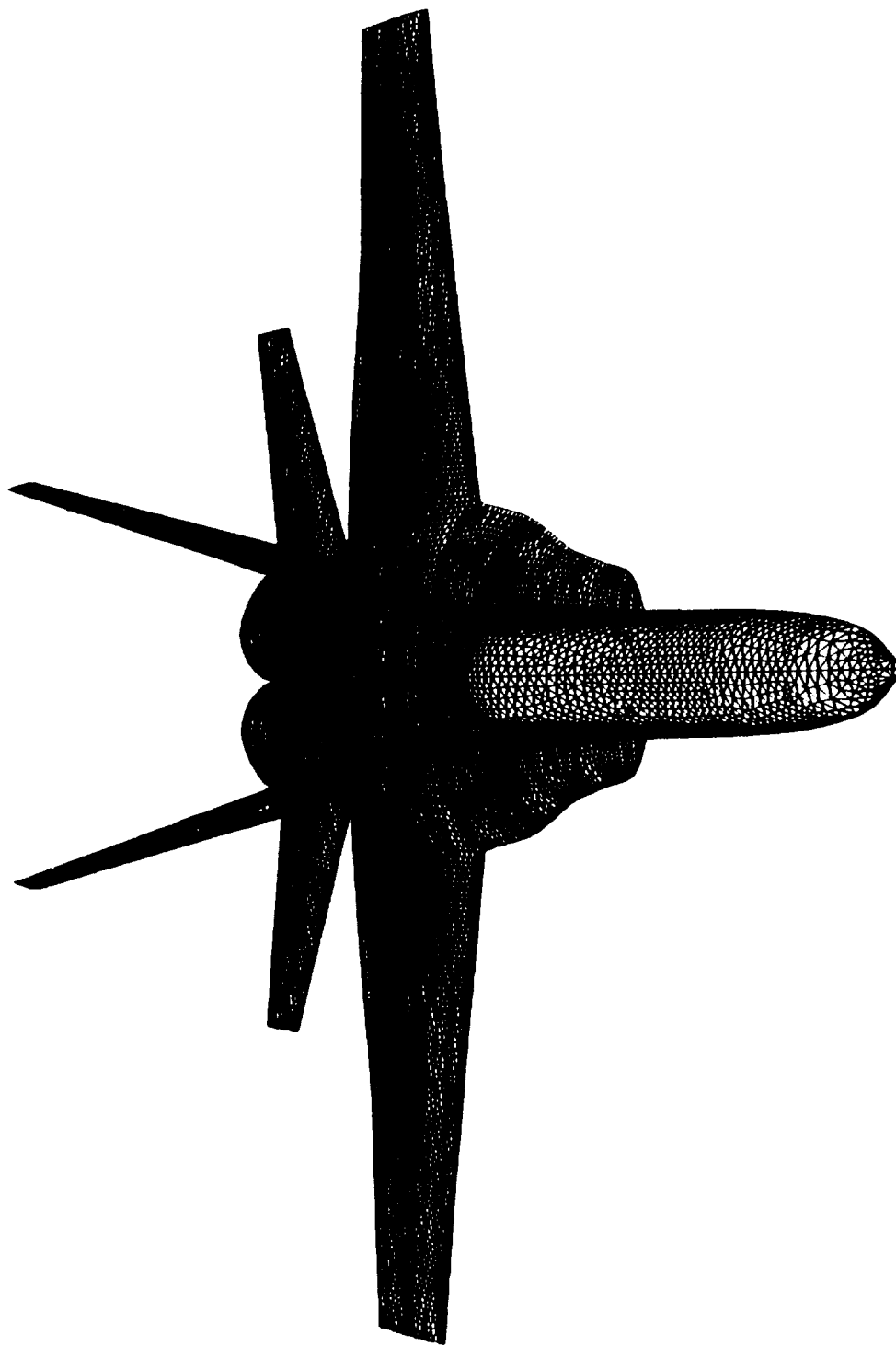


Figure 87 (b).

# DEVELOP NAVIER-STOKES ALGORITHM INCLUDING TURBULENCE MODELING FOR UNSTRUCTURED DYNAMIC MESHES

John T. Batina  
Unsteady Aerodynamics Branch

RTOP 505-63-50

**Research Objective:** The objective of the research is to develop an algorithm for numerical solution of the time-dependent Navier-Stokes equations to allow the analysis of flows involving significant viscous phenomena such as shock wave/boundary layer interaction. A turbulence model will also be developed to approximate the turbulence effects contained within such flows. These methods will be developed for use with unstructured meshes because of the advantages that the methods based on these meshes offer in comparison with the more-traditional structured grid methods. For example, with an unstructured grid, it is relatively easy to model very complicated three-dimensional geometries such as a complete aircraft configuration. With a structured grid, it is generally much more difficult to achieve this level of geometrical complexity without resorting to more sophisticated meshing methodologies (such as blocked, patched, chimera, or hybrid type grids), which in turn, significantly complicate the solution algorithm of the governing fluid flow equations. A second advantage, is that unstructured grid methods enable in a natural way, for adaptive mesh refinement to more accurately predict the physics of the flow. These methods involve enrichment and coarsening procedures to either add points in high gradient regions of the flow or remove points where they are not needed, to produce solutions of high spatial accuracy at minimal computational cost.

**Approach:** The algorithm will involve a flux-split spatial discretization for the convective fluxes of the governing flow equations and a central-difference-type approximation to treat the shear stress and heat flux terms. The flux-split spatial discretization is naturally dissipative and captures shock waves sharply with only one grid point within the shock structure. Both implicit and explicit temporal discretizations will be considered. The explicit temporal discretization is a multi-stage Runge-Kutta integration and the implicit temporal discretization is a two-sweep Gauss-Seidel relaxation procedure. For turbulence modeling, a k- $\epsilon$  model will be implemented. This turbulence model involves two coupled transport equations for the turbulent kinetic energy (k) and the diffusion rate of that energy ( $\epsilon$ ). The equations will be cast in the same form as the Navier-Stokes equations with the addition of a source term, and solved simultaneously using similar discretization procedures.

**Status/Plans:** Work on the numerical implementation of the convective fluxes of the governing equations is nearly complete and the equations describing the discretization of the viscous fluxes including a semi-analytical treatment of the boundary conditions is finished. These equations and the k- $\epsilon$  turbulence model will both be included within the algorithm in F.Y. 1991. Test cases will then be run to verify the accuracy of the capability by making comparisons of computed results with exact solutions and experimental data.

Figure 88.



# AEROSERVOELASTICITY BRANCH

F.Y. 1991 PLANS

- \*• Active Flexible Wing Program to Demonstrate Multi-input/Multi-output, Multiple Function Digital Control in TDT
- Enhanced Methods for Designing Robust, Low-Order, Digital Control Laws
- \*• Integration of Aeroelasticity and ASE into Multidisciplinary Design Methodology (HiSAIR)
- \*• Piezoelectric Materials as Dynamic Response Controllers
- Integration of Nonlinear Aerodynamics into ASE Methods
- Aero/Servo/Thermo/Elastic Assessment for NASP
- \*• Active Controls Testing Using the Benchmark Controls Model
- \*• Improved Finite Element Methods for Rotorcraft Structures
- Nonlinear Dynamic Analysis Method for Flexible Multibody Systems
- Design Optimization Studies of Tiltrotor Aeroelastic Stability
- \*• Investigation of the Effects of Large Pre-Twist Angles in Extension-Twist-Coupled Composite Blade Spars

\* Highlighted in attached figures

Figure 89.

# ACTIVE FLEXIBLE WING PROGRAM TO DEMONSTRATE MULTI-INPUT/MULTI-OUTPUT, MULTIPLE FUNCTION DIGITAL CONTROL IN TDT

Boyd Perry III  
Aeroservoelasticity Branch

and

Stanley R. Cole  
Configuration Aeroelasticity Branch

RTOP 505-63-50

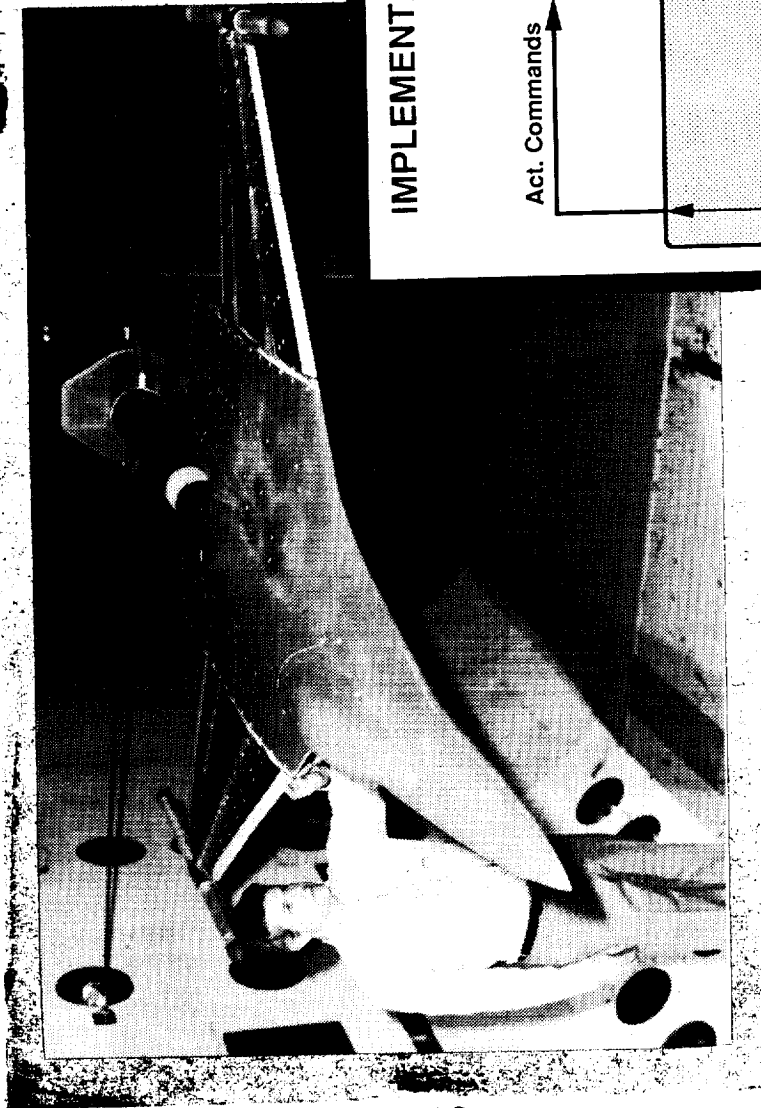
**Research Objective:** The Active Flexible Wing (AFW) Program is a joint NASA-LaRC/Rockwell International effort with the overall program goal of demonstrating multi-input/multi-output (MIMO) single-function and multi-function digital control of a sophisticated aeroelastic wind tunnel model. The single-function MIMO digital control capabilities to be demonstrated are flutter suppression, rolling maneuver load control, and rolling maneuver load alleviation. The multi-function MIMO digital control involves flutter suppression in conjunction with one of the rolling maneuver load methods. The research objective of the program is to validate analysis, synthesis, simulation, and test methodologies necessary to perform such a demonstration.

**Approach:** The approach being taken to accomplish the research objective is to design, implement, and test single-function and multi-function MIMO control concepts on the AFW wind tunnel model. The AFW model, shown at the top of the figure mounted on the sting in the Langley Transonic Dynamics Tunnel (TDT), has the capability of rolling on the sting support. This feature of the model allows for the rolling maneuver load demonstrations to be conducted. The AFW Program encompasses two wind tunnel test entries in the TDT.

**Status/Plans:** The first of these two tests occurred in the fall of 1989. During this entry, the open-loop flutter boundary of the model was determined; the digital controller was tested in all modes of operation; three single-function MIMO flutter suppression control laws were tested; and experimental data was gathered to further assist in preparing for future rolling maneuver load testing. These accomplishments were achieved with the wind tunnel model fixed to the support sting (not able to roll). One of the flutter suppression control laws demonstrated a 24% increase in flutter dynamic pressure. The second entry, planned for the late winter of 1991, will include single-function and multi-function MIMO control law testing in which the wind tunnel model will be free to roll. A block diagram showing the general setup to accomplish either single-function or multi-function MIMO control is shown at the bottom of the figure. Primary goals of the second test are to perform rolling maneuvers above the open-loop, free-to-roll flutter boundary and, further, to control and alleviate key wing loads while performing rolls above the open-loop flutter boundary.

Figure 90 (a).

# ACTIVE FLEXIBLE WING PROGRAM TO DEMONSTRATE MULTI-INPUT/MULTI-OUTPUT, MULTIPLE FUNCTION DIGITAL CONTROL IN TDT



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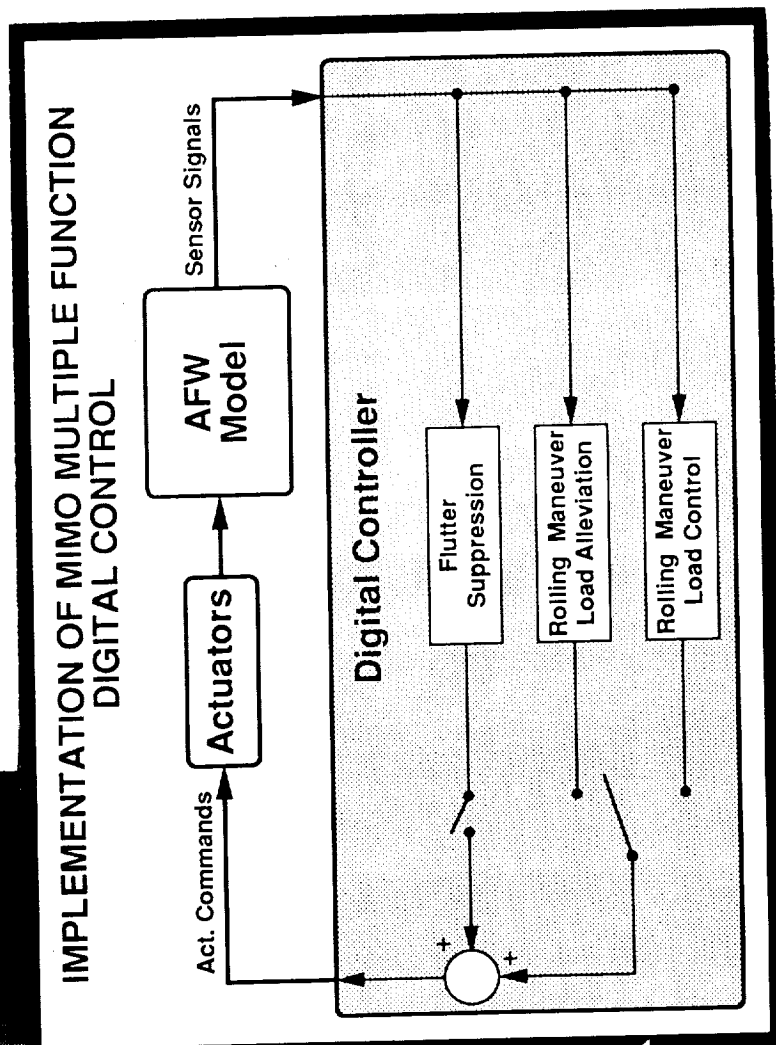


Figure 90 (b).

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## INTEGRATION OF AEROELASTICITY AND ASE INTO MULTIDISCIPLINARY DESIGN METHODOLOGY (HISAIR)

Thomas A. Zeiler (LESC), Jessica A. Woods, and Carol D. Wieseman  
Aeroservoelasticity Branch,  
James T. Howlett  
Unsteady Aerodynamics Branch,  
and  
Maynard C. Sandford  
Configuration Aeroelasticity Branch

RTOP 505-63-50

**Research Objective:** In a typical design process, aeroelasticity concerns are focused upon after considerable structural design already has been accomplished. Configurations then are analyzed to assess their aeroelastic characteristics and to determine minor modifications to correct any aeroelastic deficiencies. The objective of ASEB's participation in High Speed Airframe Integration Research (HiSAIR) is to develop methodology by which the impacts of aeroelastic and aeroservoelastic considerations may be included in the preliminary design of flight vehicles.

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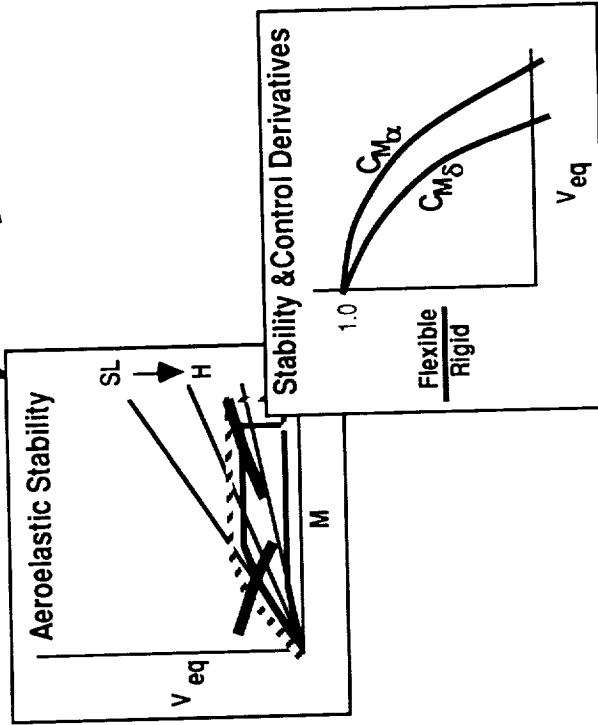
**Approach:** To achieve the research objective, ASEB will provide, to the appropriate disciplinary groups in HiSAIR, calculations of various measures of aeroelastic behavior (such as open- and closed-loop flutter and divergence speeds and flexible vehicle stability and control derivatives) as well as sensitivity derivatives of these quantities with respect to the appropriate variables. The calculations will be performed with an assemblage of new and old computer codes with expanded capabilities that have consistent data file formats.

**Status/Plans:** At present, the codes have been developed to the point where open-loop, symmetric stability boundaries and flexible stability and control derivatives can be calculated for all Mach number regimes except transonic. Some preliminary configurations were analyzed and found to be prone to longitudinal instability and degraded control surface effectiveness as a result of flexibility. ASEB also participated in the HiSAIR planning meetings where a number of specific tasks for achieving the required aeroservoelastic capability were identified. The tasks will involve further development of computer codes to handle antisymmetric cases, design control laws, analyze closed-loop behavior, and compute sensitivity derivatives.

Figure 91 (a).

# INTEGRATION OF AEROELASTICITY AND ASE INTO MULTIDISCIPLINARY DESIGN METHODOLOGY

## Preliminary Analyses



## Developing and Integrating Analysis Tools

- Subsonic (doublet lattice)
- Supersonic (ZONA, piston theory)
- Store and reuse AIC's and GAF's
- Interface with ELAPS for modal data
- Flutter, divergence, longitudinal stability & control derivatives

## Participation in Planning Team

### 9 Tasks Identified - Expanded analyses and sensitivity derivatives

- Aeroelastic stability
- Stability & control derivatives
- Open- and closed-loop

Figure 91 (b).

## PIEZOELECTRIC MATERIALS AS DYNAMIC RESPONSE CONTROLLERS

Jennifer Heeg  
Aeroservoelasticity Branch

RTOP 505-63-50

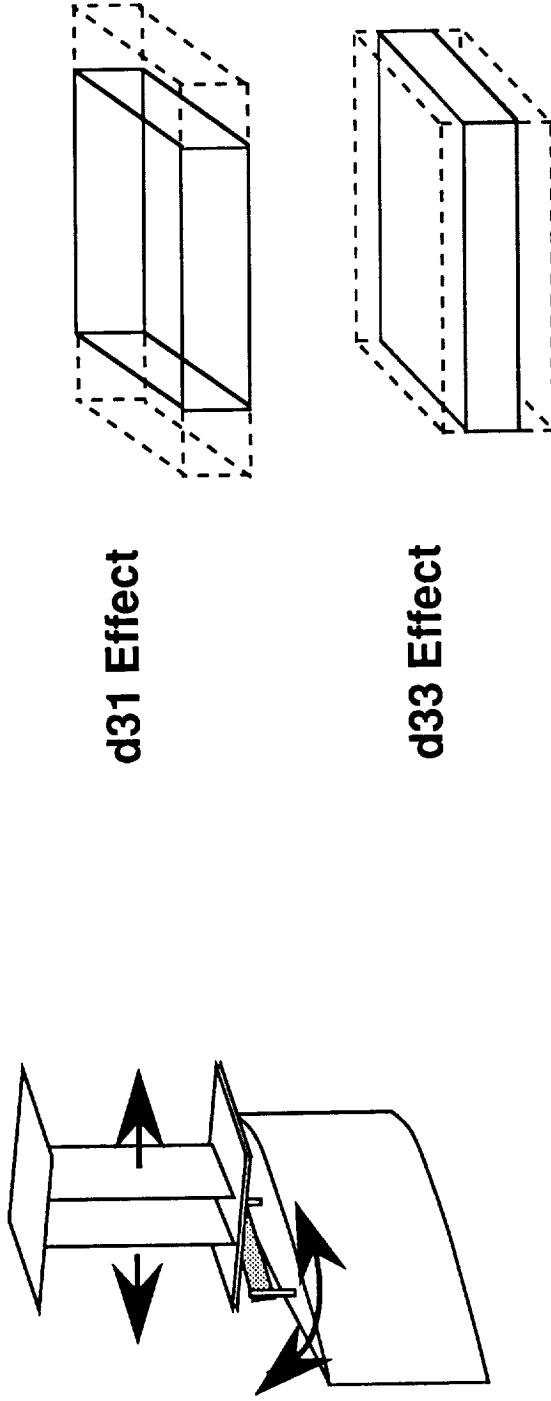
**Research Objective:** Piezoelectric plates deform mechanically when a voltage is applied between two oppositely poled faces. Similar in form to a Poisson effect, a voltage applied which causes expansion through the thickness will also cause foreshortening. Treating this voltage as the command signal from an active control law, piezoelectric ceramic plates are to be used as actuating devices to control the aeroelastic response of a system.

**Approach:** A two degree of freedom system is to be designed and constructed such that it flutters within a wind tunnel operating envelope. Piezoelectric elements are then affixed to leaf springs, each of which control the damping and stiffness properties of separate degrees of freedom. Command signals, applied independently to these elements, exert control over the damping and stiffness properties of each degree of freedom. A mathematical model of the system is to be constructed, using finite element methods, aeroelastic analysis tools, and laminated plate theory. These equations will serve as a design model for control laws; open and closed loop plant analyses, including definition of flutter characteristics, will also be performed on this model. Control laws are to be designed, with the method and order to be determined by the open loop analyses.

**Status/Plans:** A wind tunnel model, free in plunge and pitch, has been designed and fabricated based on finite element and aeroelastic calculations. A finite element model has been constructed and calculates the structural vibration frequencies and mode shapes. Unsteady aerodynamics have been generated using doublet lattice theory. These aerodynamics, mode shapes and frequencies have been used to perform an open loop flutter analysis. Ground vibration testing and open loop flutter testing are complete, the resultant natural frequencies, mode shapes and flutter velocity correlating well with the analytical predictions. Currently, several arrangements of piezoelectric plates are being investigated to determine the optimal arrangement for this application. Wind tunnel and model instrumentation are in progress, as is the debugging of the data acquisition system and digital control computer. Equations of motion are also under development, using laminate plate theory to model the piezoelectric control forces. Future plans are to perform analyses on the plant, defining properties and trends associated with the inclusion of the piezoelectric materials. Control law design and implementation will precede closed loop wind tunnel test.

Figure 92 (a).

# PIEZOELECTRIC MATERIALS AS DYNAMIC RESPONSE CONTROLLERS



**d31 Effect**

**d33 Effect**

- Piezoelectric Material Induces Changes in Local Stiffness and Damping
- Determine Ability of Piezoelectric Properties to Alter Aeroelastic Response
- Analytical and Experimental Study
- Plunge and Pitch Wind-Tunnel Model

Figure 92 (b).

## ACTIVE CONTROLS TESTING USING THE BENCHMARK CONTROLS MODEL

Carol D. Wieseman and Vivek Mukhopadhyay  
Aeroservoelasticity Branch

RTOP 505-63-50

**Research Objective:** The objectives of the Benchmark Models Program are to provide test data for evaluating the capabilities of computational aeroelasticity codes, to increase physical understanding of unsteady flow phenomenon, and to obtain test data for developing empirical design methods for those flow regimes where computational methods need further development. The Active Controls Model, one of a series of models to be tested under the auspices of this program, will include active trailing edge and spoiler control surfaces. The objectives of this particular task are to obtain steady and unsteady pressure distributions on and near the control surfaces, to measure force, moment, and control surface stability derivatives, to measure actuator performance, to design and test flutter suppression systems which use trailing edge and spoiler surfaces, and to obtain test data for assessing present state-of-the-art control law design methodologies.

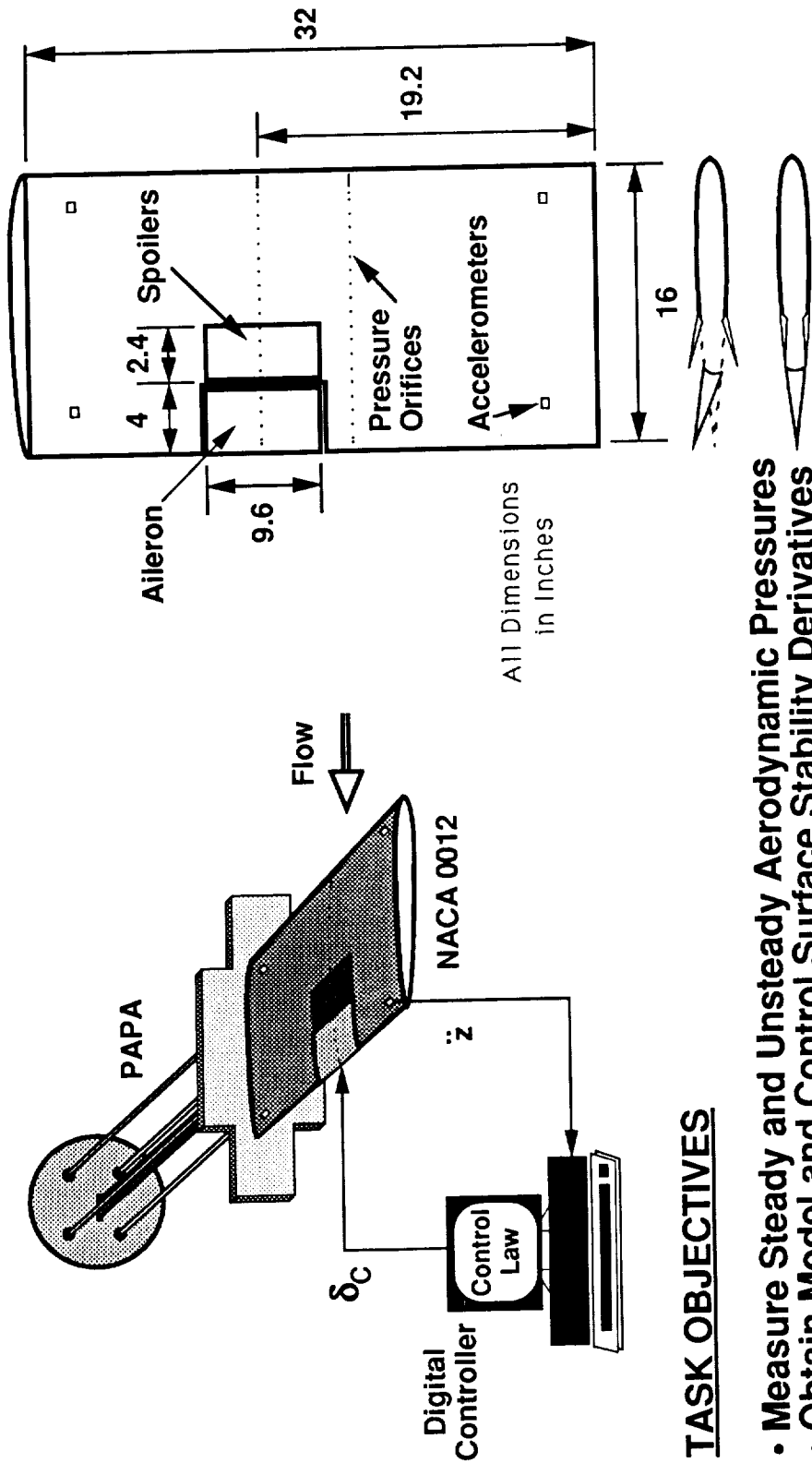
**Approach:** This research project is a cooperative team effort involving the Configuration Aeroelasticity, the Unsteady Aerodynamics, and the Aeroservoelasticity Branches of the Structural Dynamics Division. The specific role of the Aeroservoelasticity Branch in the Active Controls Model task will be to apply advanced control law design algorithms, to design, implement, and test active flutter suppression systems, and to measure data to provide validation of ASE analysis and design tools, emphasizing the activities dealing with spoiler control surfaces.

**Status/Plans:** An instrumented rigid rectangular wing model with a NACA 0012 airfoil has been previously designed, fabricated, and tested on the Pitch and Plunge Apparatus (PAPA) to measure steady and unsteady pressures. A rigid model with the same airfoil section but with an active control aileron and spoilers is presently being designed and fabricated. Design analyses were performed to obtain simple flutter suppression control laws to assist in determining the size and location of the trailing edge control surface. The control laws developed were evaluated with control surfaces of different sizes in terms of the gain and phase margins and the RMS of the control surface deflections and rates due to a random gust input. The results of these comparisons indicated that the aileron should be about 30% of the span in length and 25% of the chord in width. The surface will be located at the 60% span where pressure orifices are located to correspond to the aforementioned rigid model without the control surfaces. A more detailed design will be conducted as the model's structural properties and actuators are better known. Tests are planned to begin in early 1992.

Figure 93 (a).



# ACTIVE CONTROLS TESTING USING THE BENCHMARK CONTROLS MODEL



## TASK OBJECTIVES

- Measure Steady and Unsteady Aerodynamic Pressures
- Obtain Model and Control Surface Stability Derivatives
- Design and Test Active Control Systems
- Validate Advanced Codes
- Assess Active Controls Design Methodologies

Figure 93 (b).

# IMPROVED FINITE ELEMENT METHODS FOR ROTORCRAFT STRUCTURES

Howard E. Hinnant  
Aeroservoelasticity Branch

RTOP 505-63-36

**Research Objective:** The reduction of rotorcraft vibrations is one of the most important and difficult problems facing structural dynamicists today. To have a significant impact on reducing vibrations, without attendant weight or performance penalties, it is becoming increasingly important for vibration reduction to be considered during design. However, current finite-element-based dynamic analyses do not have sufficient accuracy to be used with confidence during design. The objective of this research effort is to develop finite element dynamic analysis methodologies which are more accurate, easier to use, and more efficient computationally.

**Approach:** Although there are several possible reasons for the lack of correlation with experiment, one that has attracted attention recently is the accuracy of the elements themselves. Most finite element codes used today employ beams with six degrees of freedom (dof's) per node, plates or shells with five dof's per node, and bricks with three dof's per node. The reason for this discrepancy among the different elements originates from the theories of elasticity which define the necessary degrees of freedom for the correct strain energies. However, one still may add degrees of freedom in the theory as long as strain energy is not modified. The ramifications of not having six dof's (three translations and three rotations) at each node on each element are interelement displacement discontinuities when using different types of elements in the same analysis. This also may happen when using only plates but in a non-coplanar model.

**Status/Plans:** A finite element program which will include beams, plates/shells, and bricks is under development. All of the elements will be developed in curvilinear coordinates such that curved and twisted geometries may be represented exactly. The elements will be anisotropic, p-version, and capable of coupling with all three rotational degrees of freedom. All displacements will be discretized using the same set of C0-type shape functions to ensure, further, displacement continuity. The resulting code will be a research tool capable of testing the effects of various assumptions and comparing the results with experimental data.

Figure 94 (a).

## IMPROVED FINITE ELEMENT METHODS FOR ROTORCRAFT STRUCTURES

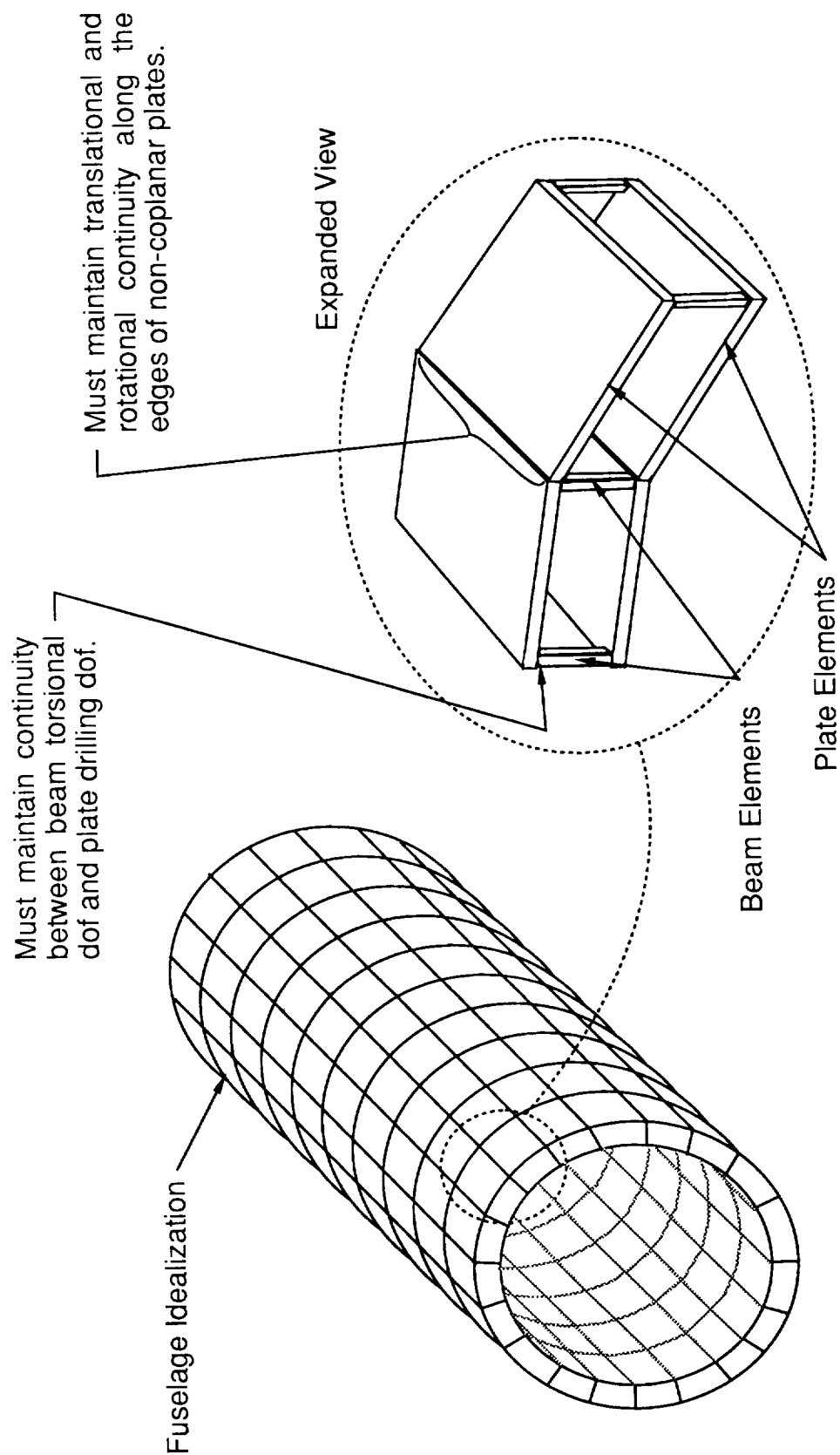


Figure 94 (b).

# INVESTIGATION OF THE EFFECTS OF LARGE PRE-TWIST ANGLES IN EXTENSION-TWIST-COUPLED COMPOSITE BLADE SPARS

Renee C. Lake and Mark W. Nixon  
Aeroservoelasticity Branch

RTOP 505-63-36

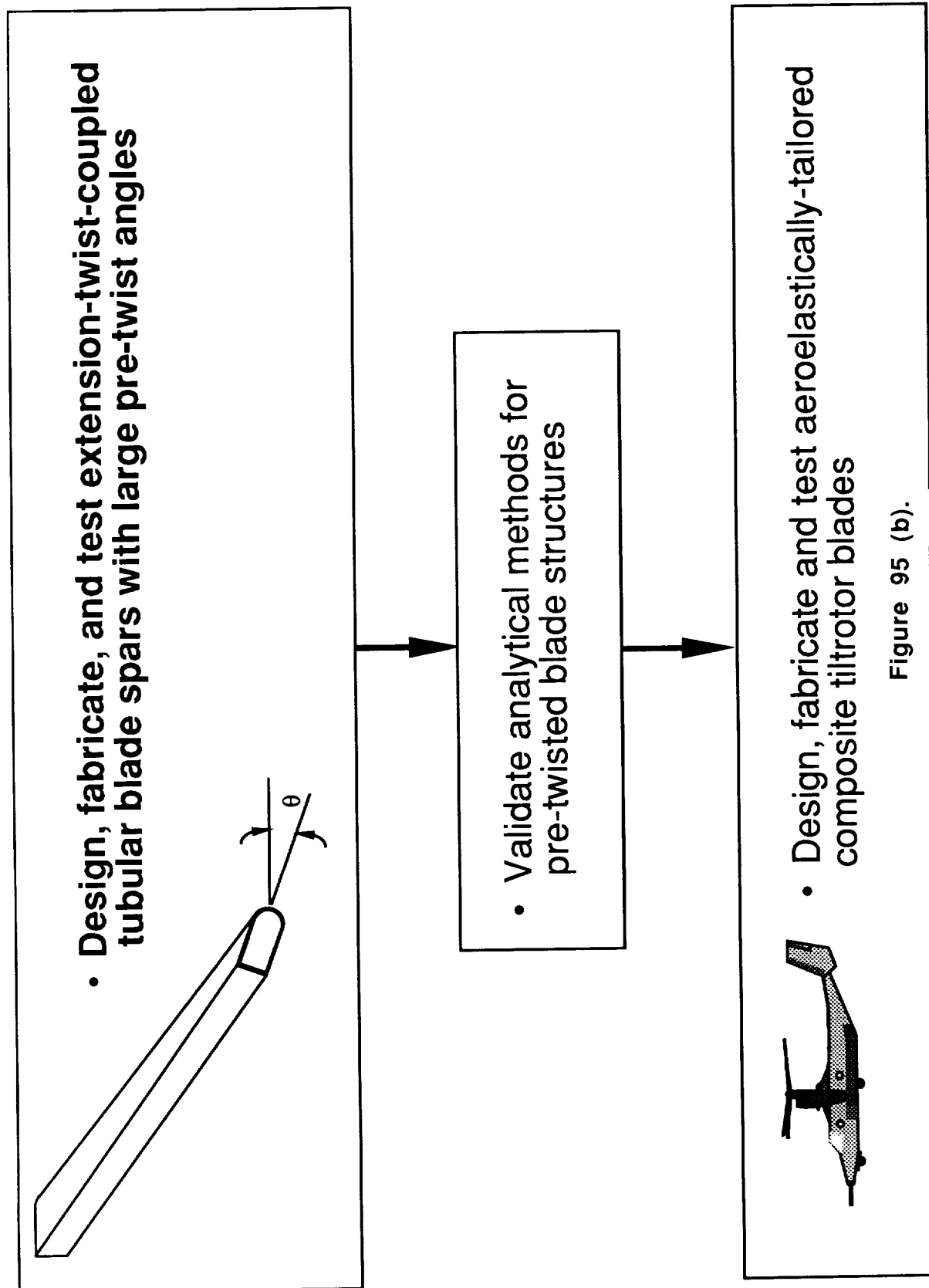
**Research Objective:** Composite materials currently are receiving significant consideration in the design of helicopter rotor blades, whereby the structural coupling associated with the ply layout angles is used to enhance the blade dynamic and aerodynamic characteristics. Recent in-house research efforts have shown that this design technology may be applied advantageously to the design of tiltrotor blades, which operate in helicopter and airplane flight modes. Since tiltrotor aircraft typically vary rotor speed by about 20% between the two flight modes, a substantial change in centrifugal force is induced along the blades and may be used to change passively the twist of extension-twist-coupled composite blades. However, the elastic twist of the blades also may be influenced by the incorporation of pre-twist into the blade geometry. This pre-twist can enhance or detract from the overall twist that is obtained, depending on the location of the initial twist axis as well as the magnitude of pre-twist. Therefore, the objective of this research is to investigate the effects of large pre-twist angles on the dynamic and aerodynamic characteristics of extension-twist-coupled tiltrotor blades.

**Approach:** This in-house research study is being conducted using the following approach: (1) design, fabricate, and test extension-twist-coupled tubular spars with large built-in twist angles; (2) validate analytical dynamics methods for analysis of pre-twisted blade structures; and (3) design, fabricate, and test aeroelastically-tailored composite tiltrotor blades.

**Status/Plans:** Current efforts are aimed at defining the geometry and cross-section design of the tubular spar, which will be representative of the primary load-carrying structure of a rotor blade. The magnitude of pre-twist incorporated in the design will represent a scaled magnitude from that of existing tiltrotor blade geometries. Tubular spars will be manufactured using graphite/epoxy in an extension-twist-coupled layout and will be subject to static as well as dynamic testing. The static testing will consist of pull tests in a tensile test fixture to determine the twist (untwist) obtained as a function of axial load. A dynamic test has been proposed in which the tubular spars would be mounted on a helicopter hub fixture and spun up to determine the twist as a function of rotor speed. This test will be conducted in a near-vacuum environment to eliminate aerodynamic effects.

Figure 95 (a).

# INVESTIGATION OF THE EFFECTS OF LARGE PRE-TWIST ANGLES IN EXTENSION-TWIST-COUPLED COMPOSITE BLADE SPARS



# LANDING DYNAMICS

## F.Y. 1991 PLANS

- Develop research plan and initiate Advanced Active Control Landing Gear Program
- Complete Phase II Heavy Rain Simulation Testing
- Complete Phase I testing of 26 x 6.6 bias-ply and radial-belted tires on smooth concrete
- Conduct ALDF tests to define normal and friction forces in rolling tire footprint
- Distribute initial version of National Tire Modeling Code to industry
- Continue development of computationally efficient algorithms for tire modeling

# **IMPACT DYNAMICS**

## **F.Y. 1991 PLANS**

- Initiate follow-on studies in scaling of composites to define various failure mechanisms
- Continue enhancement of nonlinear shell and beam composite elements in DYCAST computer code
- Evaluate effect of floor location on response of composite fuselage frame concepts
- Initiate designs for composite structures for GA composite full-scale crash test specimens
- Continue static and dynamic test program on I-, J-, and C-shaped fuselage frame concepts
- Continue development and extension of computationally efficient algorithms for composite structural analysis (UVA Grant)

# **SPACECRAFT DYNAMICS**

## **FY 91 PLANS**

### **Control Structures Interaction (CSI)**

- o Complete controls tests on Phase-0 version of Evolutionary Model
- o Complete dynamics and controls experiments on Mini-Mast
- o Make operational improvements to space structures research lab

### **Structural Dynamics Analysis And Test Methods**

- o Evaluate modal superposition on Space Station Freedom (SSF) model
- o Determine impact of SSF design changes on dynamics and control verification and on-orbit measurement requirements

### **Base Research & Technology**

- o Verify learning system identification algorithm on complex structure
- o Fabricate multi-body dynamics research model



## **INTERDISCIPLINARY RESEARCH F. Y. 1991 PLANS**

- **Basic research in optimization and sensitivity methods**
  - **Multidisciplinary optimization strategy**
  - **Aerodynamic sensitivity analysis**
- **Play key role in center-wide multidisciplinary activities**
  - **HiSAIR**
  - **Rotorcraft**
  - **CSI**
- **Produce integrated optimization capability**
  - **Aerodynamics/performance/structure for HiSAIR**
  - **Aerodynamics/dynamics/Structure for Rotorcraft**
  - **Addition of strength and buckling to CSI**

**Figure 99.**

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